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## TELEVISION WITH NIPKOW DISC AND INTERLACED SCANNING

by H. RINIA.

621.397.33

The previously described television system with a Nipkow disc for the transmission of films has now been reconstructed for interlaced scanning in order to improve the quality of the picture. A description is given of the arrangement for obtaining interlaced scanning. The synchronization required special care. In order to insure good interlacing of the reproduction, the picture synchronising signals are now derived from the Nipkow disc (instead of from the film motor). This necessitated a special synchronization of the Nipkow disc with the film *i.e.* with the mains. The method by which this problem which was solved, and which provides satisfactory damping of any fluctuations in the speed, is described in detail.

In the previous volume of this periodical[1]) a television system for film transmission was described in which a Nipkow disc was employed. In this system the picture was resolved into 405 lines which were successively scanned. Since then this apparatus has been reconstructed for interlaced scanning.

In interlaced scanning the picture, which is scanned in 1/25 sec., is again resolved into 405 lines. However the scanning light spot first scans successively all the even-numbered lines and then, when it has reached the middle of line 406, (this being the 203rd line which it scans and actually the first line of the following picture) it flies back to the middle of the first line and proceeds to scan all the lines with an odd number *(fig. 1)*. The advantage of this method lies in the fact that the picture reproduced flickers less: the effect is the same as if we had fifty complete pictures per second instead of twenty-five. The definition of the picture (fineness of the raster) is however the same as that of non-interlaced pictures with 405 lines per picture, so that the quality of the observed picture, in which both definition and freedom from flicker are important, is considerably improved.

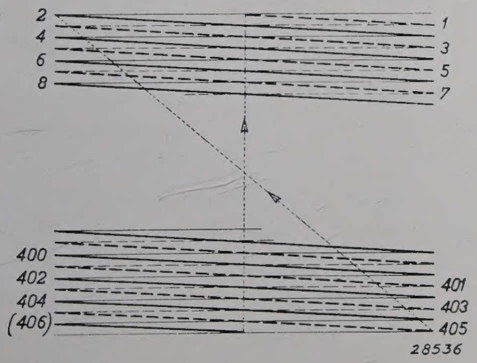

Fig. 1. Interlaced scanning with 405 lines per picture. The light spot first scans all the even-numbered lines, 2, 4, ... (heavy line). At the middle of the 406th line (*i.e.* the first line of the next picture) it flies back to the same height as at the beginning of scanning and now scans all the odd-numbered lines 1, 3, ... (dotted line), after which it again begins at the beginning of the second line. The representation here given is somewhat simplified. Actually the fly-back does not take place with infinite velocity, but it occupies a finite time. This has, however, no influence on the interlacing when the fly-back always occupies the same length of time.

### Interlaced scanning

With interlaced scanning the film is moved continuously in the same way as was described previously for non-interlaced scanning, while the holes along the edge of the Nipkow disc move past the film in a direction perpendicular to the direction of motion of the film. Since the film advances a distance of one picture in 1/25 of a second, 405 holes must move past the film in this time. This is attained by providing the disc with 81 holes and causing it to make 5 revolutions in 1/25 sec, *i.e.* 7500 revolutions per minute.

In order to illustrate the way in which interlacing is obtained, *fig. 2* shows a length of film with three pictures. The scanning light spot $L$ (*i.e.* the point at which the ray of light, coming through the hole which is just passing the film, touches the film) is in the upper left-hand side of the film picture $I$ at a height $a$. It describes an almost horizontal line toward the right; as soon as it has reached the edge it jumps to the left again (actually a new ray of light appears coming from the next hole in the disc). However, because of the continuous vertical displacement of the film (in the direction of the arrow on the left), the light spot is now slightly lower than the beginning of the first line. The second line begins at this point, and so on. If now the light spot is given a vertical motion, by means of an arrangement to be described later, opposite and equal in magnitude to that of the film, the lines are twice as far apart: after the first line, the third one is scanned. After 1/50 of a second the light spot has reached the height $b$, the upper edge of picture $II$. 1/50 of a second later the whole of picture $II$ has been scanned in $202^1/_2$ lines, and the light spot is at $c$, which point has also been reached by the upper edge of picture $III$, while the upper edge of $II$ now lies at $a$. If at this moment the light spot jumps back to $a$, picture $II$ is scanned once more. The fly-back of the light spot to the upper edge of the picture takes place after exactly $202^1/_2$ lines, *i.e.* at a moment when it is exactly in the middle of a line. The section of film has at that moment advanced only one half the distance between the lines since the beginning of the last line. Therefore the lines of the second scanning of picture $II$ lie exactly symmetrically between the first $202^1/_2$ lines scanned. In this way interlaced scanning is achieved.

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[1]) H. Rinia and C. Dorsman, Philips techn. Rev. 2, 72, 1937.

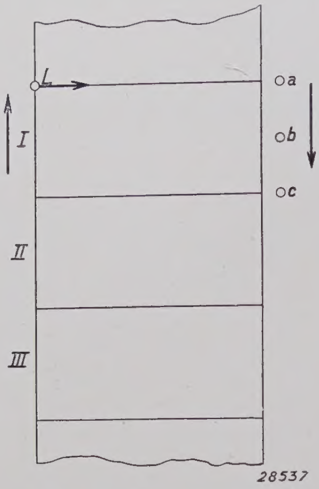

Fig. 2. Interlaced scanning of the film. The section of film moves in the direction of the left-hand arrow. The light spot $L$ is projected through the holes in the Nipkow disc which move across the film picture. The light spot must be given a vertical motion equal and opposite to the motion of the film (arrow, right), and it must jump from the height $c$ to $a$ periodically.

The vertical motion of the light spot is obtained in the following way *(fig. 3)*. The light ray which passes through a hole in the Nipkow disc $N$ passes through the objective $O$ and falls upon a mirror $S$ which reflects it back to the film $F$. The mirror can be rotated about an axis $a$, which is perpendicular to the plane of the drawing and lies in the plane of the mirror surface. A lever $h$ is attached to the mirror and its extremity is pressed by a spring $v$ against the cam disc $K$. The cam disc is driven by the film motor and makes one revolution in the time in which one picture passes, *i.e.* 1500 revolutions per minute. The circumference of the disc $K$ has such a shape that the mirror, and therefore also the reflected light spot scanning the picture, is given exactly the motion described above.

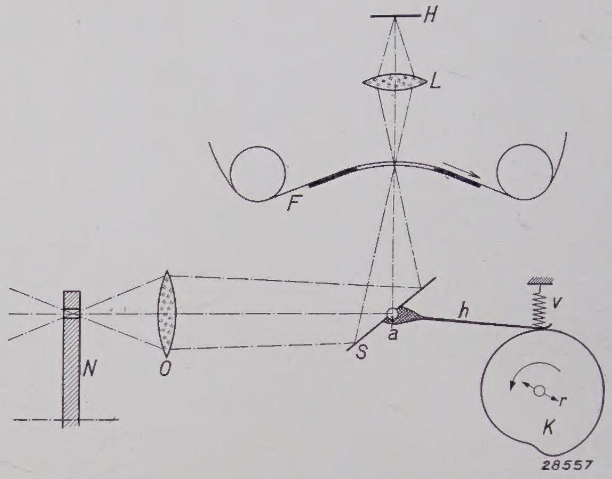

Fig. 3. Arrangement for obtaining interlaced scanning of films. $N$ = Nipkow disc. $O$ = lens which focusses the images of the holes in $N$ sharply on the film $F$. The mirror $S$ can be rotated about the axis $a$ (perpendicular to the plane of the drawing) and is given a dipping motion by the lever $h$, which is pressed by the spring $v$ on the circumference of the cam disc $K$. The axis of the cam $K$ can be shifted slightly with a very fine setting screw in the direction of the arrows $r$. In this way the amplitude of the motion of the mirror may be accurately regulated. Lens $L$ focusses the image of the opening of lens $O$ on the photocathode $H$ of the electron multiplier which amplifies the picture signals.

*Fig. 4* shows the development of the disc, *i.e.* the radius as a function of the angle. The curve at the same time represents approximately the angle of rotation of the mirror and consequently the displacement in height *(fig. 2)* of the scanning spot as a function of the time [2]). It may be seen that the light spot is displaced uniformly during part $I$ of one revolution of disc $K$, and during the very short part $II$ it flies back to its initial position. This jumping back of the mirror must take place during the time of the picture synchronization signal which is transmitted between two successive pictures of the film (in this interval scanning would be useless in any case). The picture synchronization signal however occupies only 0.002 sec. In order to have the mirror jump back in such a short time without the appearance of any very large forces of inertia, the moment of inertia of the mirror, of its holder, and especially of the lever $h$, must be made very small. The mirror is no wider than is necessary for the required movement of the scanning spot, and the lever is made short and as light as possible for the necessary stiffness. The length of the lever cannot be made indefinitely short since the tolerances of the cam disc and its bearings would otherwise become too small. In our case the lever is 32 mm long, the tolerances are $\pm 3 \mu$ and the acceleration at the end of the lever is 300 times the acceleration due to gravity. The mass of lever and mirror together acting at the end of the lever is only 0.5 g. The shape of the cam disc in part $II$ of the curve in fig. 4 is such that the lever is uniformly accelerated during the first half of this period and then slowed down in the same way. This may be seen in *fig. 5.* (This line is actually the second derivative of the curve in fig. 4.) In this way shocks are avoided and the mechanism runs fairly noiselessly.

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[2]) This is not absolutely true because the point of contact between lever and cam disc experiences a slight sideward motion in the rising and falling of the lever; this has been taken into account in determining the shape of the cam disc. The cam therefore has not exactly the shape represented in fig. 4, but such a shape that the angle of rotation of the mirror as a function of the time varies according to fig. 4.

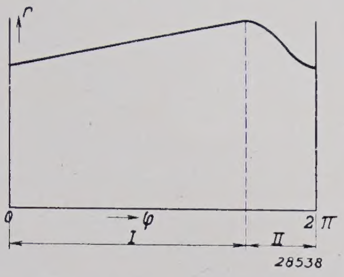

Fig. 4. Fundamental form of the development of the cam disc $K$ (radius $r$ as a function of the angle $\varphi$). The curve also gives the variation of the displacement of the light spot on the film with the time. In part $I$ scanning takes place, in part $II$ the back flash.

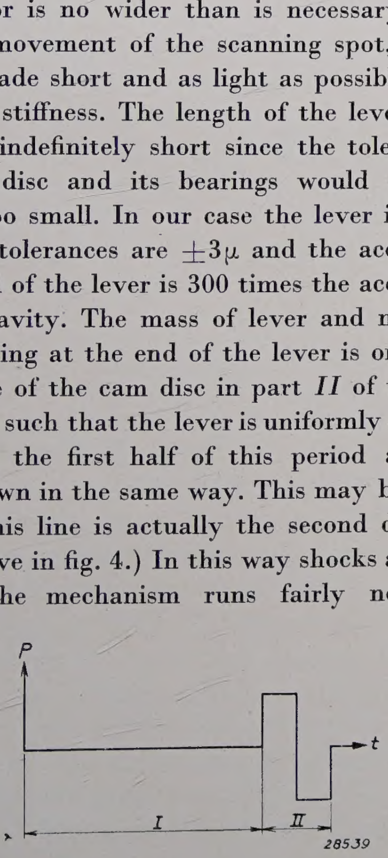

Fig. 5. Variation of the force of inertia $P$ on the extremity of the lever $h$ during one revolution of the cam disc $K$ (this line is approximately the second derivative of the curve of fig. 4).

The spring $v$ must of course be strong enough to prevent the lever from leaving the cam disc at any point [3]).

### Image on the photocathode

The path of the film $F$ at the point where the pictures are scanned is part of the surface of a cylinder whose axis coincides with the axis about which the mirror turns. Because of this the image of the light spot on the film always remains sharp when the mirror turns. The light transmitted through the film is collected by lens $L$ and thrown upon the photocathode $H$ of the electron multiplier which amplifies the picture signals. It is essential that the image of the light spot shall always fall upon the same points of the photocathode, so that, so to say, the photocathode remains unaware of the fact that the scanning spot comes continually from different directions. The sensitivity of a photocathode is never constant over its entire surface, so that if the light spot were displaced on the photocathode during scanning, the proportionality factor between film transmissibility and excited signal current would not be the same for all points of the picture. Such a displacement can be prevented by focussing with lens $L$ an image on the photocathode of the opening of lens $O$, where the distribution of brightness is independent of the direction of the rays, so that the image of a point $P$ of this opening always falls upon the same point of the photocathode. In previous arrangements without the rotating mirror in the path of the rays, this could be achieved directly. The fan-shaped beam of rays lying in one plane, which has its origin at $P$ (the fact that the rays appear successively instead of simultaneously is of no importance here), may be concentrated by an ordinary spherical lens to a point again. By the action of the dipping mirror, however, the beam of rays takes on another form. This is represented in *fig. 6*, in which for the sake of simplicity the centre point of the opening of lens $O$ is chosen for the point $P$. In fig. 6$a$ a definite position of the mirror is assumed; due to the reflection the horizontal "fan" is transformed into a vertical "fan" with the image $P'$ of point $P$ as origin. Point $P'$ might again be projected upon the photocathode with an ordinary lens. Due to the dipping motion of the mirror, however, about the axis $a$ the vertical "fan" as a whole is given a rotating motion about the same axis. The origin $P'$ describes approximatelly a line $p$ which lies in a plane perpendicular to $a$. Thus the beam of rays finally assumes the form shown in fig. 6*b*: it narrows twice to a line, in $a$ and $p$; the two lines are perpendicular to each other. For every other point of the opening of $O$ a similar figure is obtained which differs only slightly from that for the centre $P$.

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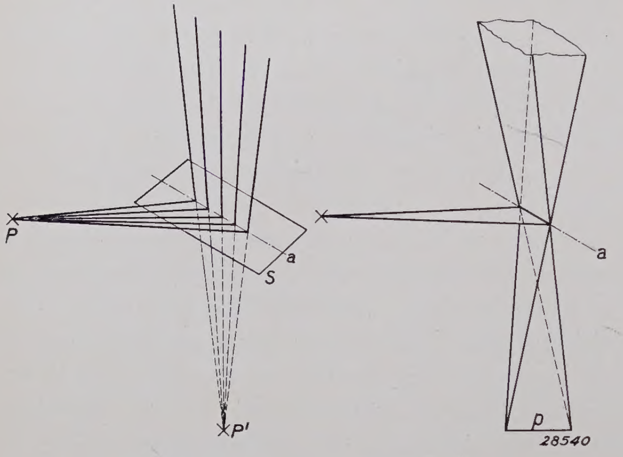
[3]) By giving the cam disc a somewhat more complicated shape it is also possible to scan the film pictures alternately twice and three times. With 24 pictures per second one then obtains exactly 60 scannings per second. This is desirable for countries like the United States where the mains voltage has a frequency of 60 c/s (instead of 50 c/s as in this country). Due to the synchronism of scanning and mains voltage many disturbing phenomena are avoided.



a b

Fig. 6. The fan-shaped beam of rays which originates from a point $P$ of the opening of the lens $O$ (see fig. 3) assumes a different form due to the dipping mirror $S$.
a) At a definite position of the mirror the horizontal fan is transformed into a vertical one.
b) By the motion of the mirror the vertical fan is turned back and forth around the axis $a$, the image $P'$ describes a line $p$. The resulting beam narrows twice, at $a$ and $p$, to a line.

It is known from elementary optics that the image of a point through an astigmatic lens is not a single point, but two mutually perpendicular lines lying one behind the other. Since in every optical arrangement the path of the rays may be reversed, it is clear that a beam of rays which has as origin two mutually perpendicular lines one behind the other, *i.e.* the form of fig. 6*b*, can be focussed to a definite point by means of a suitable astigmatic lens. This fact has been applied in the case under consideration. The astigmatism consists of the different curvature of the surface of a lens in two mutually perpendicular directions. Such a lens is obtained here by combination of a spherical with a cylindrical lens. One surface of both lenses is plane. By cementing the two plane surfaces together loss of light due to reflection is avoided as far as possible.

## Synchronization

In the transition from ordinary scanning to interlaced scanning especial attention had to be paid to synchronization. We must distinguish here between the interlacing of the scanning and that of the reproduction.

### *Interlacing in scanning*

In order to obtain satisfactory interlacing in scanning, *i.e.* in order to make the set of lines of the second scanning of a picture always fall symmetrically between the lines of the first scanning, the first requirement is that the dipping of the mirror shall take place synchronously with the changing of the film pictures. This is achieved mechanically due to the fact that the film and the cam disc are driven by the same motor (a synchronous motor of 3 000 revolutions per minute connected to the mains). When the adjustment is once correctly made the jumping back of the mirror always occurs at the right moment. In addition, however, the amplitude of the motion of the scanning spot, *i.e.* the distance $a$-$c$ in fig. 2, must be exactly equal to the distance between corresponding points of two successive film pictures (the height of a picture plus the distance between two successive pictures). If this were not so, then, according to the explanation given with fig. 2, a different part of the picture would be scanned in the first scanning than in the second scanning, while these different parts would fall upon the same places in the picture reproduced. In order to be able to fulfil the above condition in every case, even when the height of the film pictures has been somewhat altered by shrinkage or stretching of the film as a whole, the axis of the cam disc (see fig. 3) can be shifted in position. By means of a fine set screw its distance from the axis of the mirror can be varied slightly. The effective length of the lever $h$ is hereby changed and it is therefore possible to regulate accurately the angle through which the mirror turns during one revolution of disc $K$.

### *Interlacing in reproduction; picture synchronization signals*

For satisfactory interlacing of the reproduction it is necessary that the times of the picture synchronization signals be very accurately determined with respect to the line synchronization signals: the light spot on the fluorescent screen of the receiver must at the moment of fly-back be alternately exactly at the end and exactly in the middle of a line (see fig. 1). In order to obtain some idea of the requirements to be met, it must be remembered that the scanning of one line lasts about 1/10 000 of a second. The time of the picture synchronization signal may only exhibit fluctuations which are small with respect to this time interval. A discrepancy of 1/10 of the length of a line, *i.e.* 1/100 000 of an second is already observable in reproduction as an asymmetry in the position of the two sets of lines.

Since the line synchronization signals are obtained through the holes in the Nipkow disc, as previously described ¹), it seemed natural to insure the correct mutual phase relation of line and picture synchronization signals in a simple way by deriving the picture synchronization signals also from the rotating disc. The following arrangement serves to do this (see *fig.* 7). A disc $B_1$ is attached to the axis of the Nipkow disc. Two sectors, each of 90°, and diametrically opposite each other are cut out of the disc $B_1$. On opposite sides of $B_1$ are placed a lamp $D_1$ and a photocell $E_1$. The light from the lamp is interrupted twice during one revolution of the disc, *i.e.* 250 times per second; the light flux $I_1$ on the photocell varies as shown in *fig. 8a*. In series with $E_1$ is a second photocell $E_2$, upon which the light from lamp $D_2$ falls. The light from $D_2$ is interrupted periodically by a disc $B_2$. This disc is driven by a small synchronous 3 000 r.p.m. motor $S$ connected to the mains. Disc $B_2$ has only one opening of such a width that the transmitted light impulses last somewhat longer than the light impulses from disc $B_1$. The light flux $I_2$ on photocell $E_2$ varies as shown in fig. 8*b*. In the electrical circuit which includes the two photocells in series, a current can however flow only at moments when both photocells are illuminated, which is the case at every fifth impulse of the light flux on $E_1$ (fig. 8*c*). In this way 50 impulses per second are obtained which, due to the unchanging relative positions of disc $N$ and $B_1$, always have the same phase relation relative to the line synchronization signals. These impulses are used as picture synchronization signals.

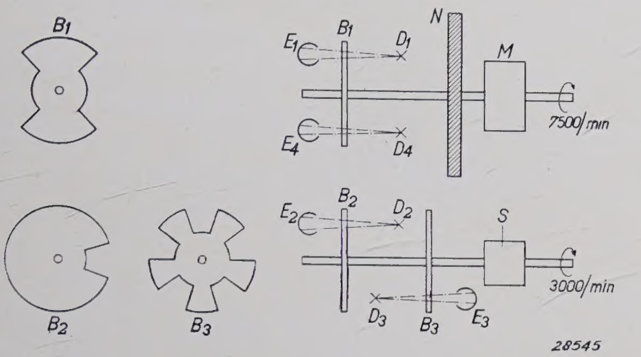


Fig. 7. Arrangement for obtaining picture synchronization signals. $M$ = collector motor which drives the Nipkow disc, $S$ = synchronous motor connected to the mains. $B_1$, $B_2$ = sector discs, $D_1$, $D_2$ = lamps, $E_1$, $E_2$ = photocells. The sector disc $B_3$ and the photocells $E_3$, $E_4$ with their lamps serve for synchronization of the Nipkow disc with the mains, as described on page 294.

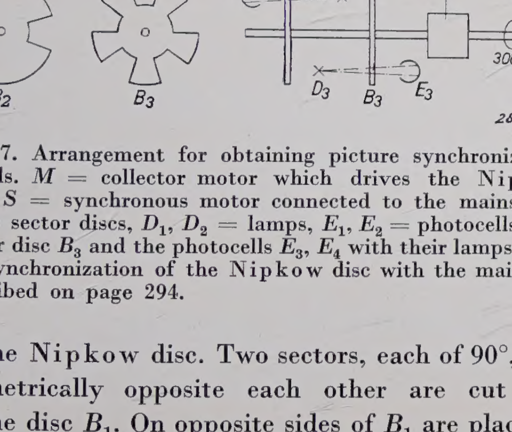


Fig. 8. Production of the picture synchronization signals. The light fluxes $I_1$ and $I_2$ on the photocells $E_1$ and $E_2$ in series with each other (see fig. 7) are interrupted by the discs $B_1$ and $B_2$ in the rhythm shown in the drawing. The light flux $I_1$ consists of 220 impulses per second (*a*), the light flux $I_2$ of 50 (*b*). The resultant photocurrent $i_{1,2}$ consists of 50 impulses per second (*c*) each lasting 0.002 of a second. These impulses are used as picture synchronization signals.

In the earlier arrangement ¹) the picture synchronization signals were obtained by a rotating sector on the axis of the film motor which interrupted the light falling on a photocell in the desired rhythm. This arrangement is now used to suppress the picture signal during the time when the picture synchronization signal is being transmitted. The impulses of the photocurrent, which are somewhat wider than the picture synchronization signals, are amplified and fed to one of the plates of the electron multiplier which amplifies the picture signal. By such a large voltage impulse on one of the plates, the secondary emission of that plate is interrupted since electrons no longer fall upon it; the amplification of the whole mutiplier thereby immediately becomes zero ⁴). The picture signal is therefore suppressed during the voltage impulse. and the magnitude of the picture synchronization signal is consequently constant.

## Synchronization of the Nipkow disc.

Because of the fact that the picture synchronization signals are now no longer derived from the film motor as in the previous arrangement, but from the Nipkow disc, a special synchronization became necessary between the film and the Nipkow disc. In order to attain correspondence between the picture scanned and the picture reproduced, the picture synchronization signals must be synchronous with the changing of the film pictures. A deviation from the correct ratio of revolutions of film motor to those of the Nipkow disc

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⁴) One particularly satisfactory characteristic of the electron multiplier is the fact that, due the absence of a current when the multiplier is not illuminated, no extra voltage impulse occurs (in contrast to the case of an ordinary amplifier valve).

(actually disc $B_1$, see fig. 4), would lead to the reproduced picture being not stationary but moving over the screen. The Nipkow disc must therefore be synchronized with the film motor and in such a way that no appreciable fluctuations occur about an average value of the speed, in order the prevent a disturbing rise and fall of the picture [5]).

The problem of keeping the number of revolutions of the Nipkow disc constant, at 7 500 revolutions per minute as mentioned above, is made more difficult by the fact that due to the large moment of inertia of the disc, the characteristic frequency at which the system can oscillate becomes low (of the order of 1 c/s). The oscillations occurring cannot therefore be satisfactorily suppressed by an eddy current damping in the driving motor, but would have to be avoided by the use of a sufficiently powerful motor [6]). Apart from the fact that the use of a very heavy motor would not be exactly an elegant solution of the problem, the synchronizing of the asynchronously starting motor is also difficult.

A very satisfactory solution was obtained in the following way. The axis of the Nipkow disc $N$ is driven by a commutator motor. On opposite sides of the sector disc $B_1$ (fig. 7), which serves for the excitation of the picture synchronization signals, there is a second photocell $E_4$ and a lamp $D_4$. The light flux $I_4$ on $E_4$ again has the form of fig. 8*a* with 250 impulses per second, or 15 000 per minute (see *fig. 9a*). On the axle of the synchronous motor $S$ (see fig. 7), besides disc $B_2$, there is also a second disc $B_3$, out of which 5 sectors have been cut, so that the light falling on the photocell $E_3$ is interrupted in the same rhythm (15 000 times per minute) as the light on photocell $E_4$. The light flux $I_4$ on photocell $E_4$ varies as shown in fig. 9*b*. Photocells $E_3$ and $E_4$ are again connected in series, a photocurrent flows only when both of them are illuminated at the same time. A pulsating-direct current $i_{3,4}$ occurs (fig. 9*c*), whose average strength obviously depends upon the phase relation between discs $B_1$ and $B_3$. By means of the current $i_{3,4}$ the excitation of the commutator motor $M$ which drives the Nipkow-disc, is regulated as follows (see *fig. 10*). The pulsating direct current, which is smoothed by the condenser $C_1$, causes a fall in potential along the resistances $R_1$ and $R_3$. The fall in potential along $R_3$ acts, over $R_2$, between grid and cathode of the triode $F$. The anode current of $F$ causes a voltage drop along the resistance $R_4$. This voltage influences the moment of ignition of a relay valve $G$ which supplies the excitation current of the motor $M$ (actually three relay valves are connected in parallel for the three phases of the supply current). An alternating voltage $V_g$ is supplied to the grid of $G$ by the transformer $L$, which voltage is 90° in phase behind the anode alternating voltage $V_a$ (*fig. 11*). The anode current flows only from the moment $t_1$ when the grid voltage becomes positive until moment $t_2$ when the

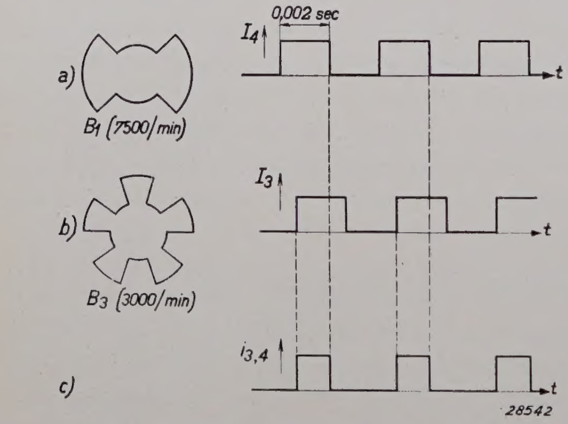

Fig. 9. a) Variation with time of the light flux $I_4$, falling on the photocell $E_4$ and periodically interrupted by the disc $B_1$.
b) Variation with time of the flux $I_3$, falling on the photocell $E_3$ and periodically interrupted by the disc $B_3$.
c) Variation with time of the resultant photocurrent $i_{3,4}$ at a definite relative phase displacement of the discs $B_1$ and $B_3$.

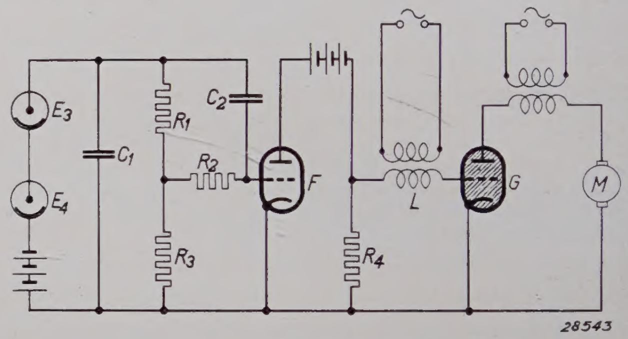

Fig. 10. Diagram showing the principle of the circuit for synchronization of the Nipkow disc. $E_3$ and $E_4$ = photocells, $C_1$ = smoothing condenser for the photocurrent $i_{3,4}$. The voltage on $R_3$ is amplified in the valve $F$. The voltage on $R_4$ is fed to the grid of the relay valve $G$ which supplies the excitation current for the motor $M$ which drives the Nipkow disc. The transformer $L$ supplies a sinusoidal grid voltage to $G$ which is 90° in phase behind the anode voltage. Due to the resistance $R_2$ and the condenser $C_2$ the regulatory photocurrent obtains the necessary forward phase shift with respect to the deviation occurring from the correct number of revolutions of the disc at that frequency at which the system can oscillate.

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[5]) A slight rise and fall of the picture, as sometimes also occurs in the picture in a cinema, is not disturbing.

[6]) In any case it would not be possible to use an ordinary synchronous motor connected with the mains, since such a motor makes 3000 r.p.m at most. A synchronized converter from 50 to 125 c/s would have to be employed.

anode voltage $V_a$ becomes negative. If now a direct voltage is superposed on the grid voltage $V_g$, the curve $V_g$ in fig. 11 is shifted somewhat in height and the moment $t_1$ occurs somewhat sooner. The anode current impulses from $G$ become longer, *i.e.* the average anode current which excites the motor $M$ becomes greater, the motor runs faster. Therefore the speed of the motor is influenced by the magnitude of the photocurrent $i_{3,4}$, *i.e.* by the phase relation of the discs $B_1$ and $B_3$ in fig. 7 and 9. At a definitive position of the discs $B_1$ and $B_3$ the beginning of a relative speeding up of the Nipkow disc will result in a decrease in the photocurrent $i_{3,4}$ and therefore also in a retarding influence on the disc. Nevertheless this system would not be sufficient without additional precautions not only to obtain synchronization but also to prevent oscillations. The synchronizing force is in phase with the deviation which occurs in the relative position of the discs $B_1$ and $B_3$, and by which, as in the case of the pendulum where the force in the backward direction is in phase with the displacement from the mean relative position of the discs, *i.e.* synchronism of motion, (the position of rest of the pendulum) is established, but no damping is obtained. In the case of the pendulum for damping a frictional force is necessary which is always a quarter of a period in phase ahead of the backward-acting force of gravitation. By analogy with this in our synchronization arrangement also the synchronizing force must be a certain amount ahead in phase of the deviation from the correct relative position. This is realized in a simple way by means of the condenser $C_2$ in fig. 10, which is of such a size that the voltage variations fed to the grid of $F$ are ahead in phase by a certain amount with respect to the variations of the photocurrent $i_{3,4}$ at that frequency at which the Nipkow disc can oscillate.

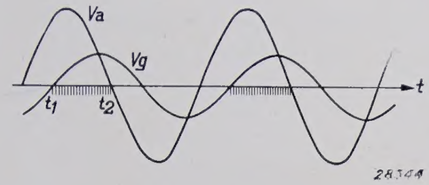

Fig. 11. The relay valve $G$ (fig. 10) ignites as soon as the grid voltage $V_g$ becomes positive (time $t_2$). The valve works only during the time intervals indicated by cross hatching. If a direct voltage is superposed on $V_g$, *i.e.* if the curve $V_g$ is raised somewhat in height the moments $t_1$ occur somewhat sooner, the average anode current of the relay valve becomes greater.

Excellent damping and synchronization is actually obtained in this way. With any slight changes in the mains frequency, the Nipkow disc, due to the action of the synchronous motor $S$, continues to move synchronously with the film which is in turn moved synchronously with the mains.

# THE "ROTALIX" TUBE FOR X-RAY DIAGNOSIS

by J. H. VAN DER TUUK.

621.386.1 : 616-073

In X-ray tubes for medical diagnosis in which moving organs (heart, lungs, stomach) are to be photographed, a very high specific focus loading of very short duration is essential. In contrast to the case of the previously described tube for the investigation of crystal structure, an intensive cooling with running water would be quite inadequate here. The specific loading can however be considerably increased by allowing the anode to rotate during the exposure. The improvement obtained by this method and the manner in which this idea is realized in the "Rotalix" tubes are discussed in this article.

## Sharpness of the X-ray picture

As in ordinary photography, sharpness is also essential in X-ray photography. In medical X-ray examination the primary problem is to obtain sharp pictures of certain parts of the body or organs. What are the requirements which must be made of an X-ray tube for this purpose, and how is the desired tube to be realized technically? The problems here are somewhat different from those in the case of the recently described X-ray tube for crystal structure analysis.

It is clear that the size of the focus of the X-ray tube plays an important part. Let us assume for the sake of simplicity that the focus is at $d = 1$ metre distance from the object to be photographed; the distance object-to-film may be $e = 10$ cm (*fig. 1*). The lack of definition with which a point of the object is projected as a shadow image on the film is then 10 per cent of the dimensions of the focus; if the focus is 3 mm wide a point is projected as a spot 0.3 mm in diameter. From this one might conclude that the X-ray tube with the smallest focus gives the sharpest picture (at definite values of $d$ and $e$; by increasing $d$ the geometrical lack of definition is decreased in any case). This is indeed approximately true in the photography of simple fractures, and in general in the photography of stationary objects.

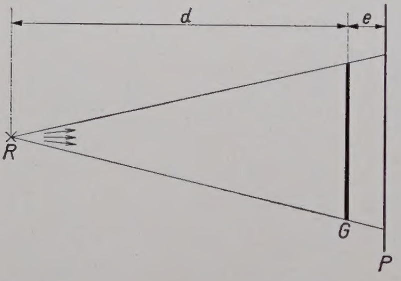

Fig. 1. Arrangement in taking an X-ray photograph. The object $G$ is at a distance $d$ from the square focus $R$. The distance between object and film $P$ is $e$. With an area $F$ of the focus every point of the object is projected as a shadow spot of width $e\sqrt{F}/d$ (geometrical lack of sharpness $O_g$).

The situation, however, is quite different if the object to be photographed moves during the exposure, as in the case of heart, lung and stomach photographs. In addition to the geometrical lack of definition of the picture due to the finite dimensions of the focus, the so-called kinematic lack of definition plays a part. The most rapidly moving parts of the lung move for instance at a speed of 15 mm/sec [1]). The lack of sharpness caused by this movement depends upon the exposure time, and may be very considerable. In order to limit the kinematic lack of sharpness the necessary exposure time must be made as short as possible, which means that at a definite permissible loading per sq.cm. of the focus the surface of the focus would have to be increased in order to obtain a greater intensity. Thus we make two contradictory requirements of the focus: it must be small in order to keep the geometric lack of sharpness ($O_g$) small, and it must be large in order to keep the kinematic lack of sharpness ($O_b$) within certain limits. The total lack of sharpness [2]) $O = O_g + O_b$ is as small as possible when:

$$O_g = 2\,O_b \quad \cdots\cdots\cdots \quad (1)$$

This may be explained as follows. The kinematic lack of sharpness $O_b$, with the very short exposure times $t$ to be considered, is proportional to these times: $O_b = a.t.$ The geometrical lack of sharpness $O_g$ is proportional to the linear dimensions of the focus, *i.e.* to the square root of the area $F$ of the focus: $O_g = b \cdot \sqrt{F}$ is however proportional to the total intensity of the X-radiation, and therefore inversely proportional to the necessary exposure time $t$; therefore $O_g = c/\sqrt{t}.$ The total lack of sharpness becomes $O = O_b + O_g = a.\,t. + c/\sqrt{t}.$ $O$ reaches a minimum for the case when $a - (1/2\,t) \cdot c/\sqrt{t} = 0$, *i.e.* when $c/\sqrt{t} = 2 \cdot a\,t$, *i.e.* condition (1).

With a given exposure technique and a given speed of the object to be photographed, for a given distance between focus and object, the most favourable size of the focus of the X-ray tube to be used is determined by equation (1). (For more slowly moving objects a smaller focus is in every case still more satisfactory).

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[1]) H. Chantraine, Fortschr. Röntgenstr. **9**, 659, 1933.

[2]) The lack of sharpness of the picture due to the photographic material is here left out of consideration.

[3]) A. Bouwers, Acta Radiologica **12**, 175, 1931.

If the distance $d$ between focus and object (fig. 1) is changed, then the optimum area for the surface of the focus is also changed. The attainable sharpness however remains the same. If we choose the dimensions of the focus twice as great, the total intensity will of course become 4 times as great; however, in order to obtain the same geometrical sharpness we must decrease the area of the focus by one half, and the intensity of the X-radiation becomes one fourth, so that we have gained nothing in the end.

### Specific loading

The sharpness of the picture, as far as the X-ray tube is concerned, can only be improved according to the above by simultaneously diminishing the area of the focus and shortening the exposure time. This is possible if we can increase the load per sq.cm. on the focus. This specific loading has however a natural limit due to the maximum permissible temperature of the focus. As in the previously described X-ray tube for structural analysis [4], the problem is here encountered of how to make the specific loading as high as possible without overheating the focus. The solution reached in that case (cooling with running water) is not satisfactory in our case. The exposure times in structure analysis are always at least several minutes, while in the X-ray photography of moving organs we are often concerned with exposure times of only several hundredths of a second. The loading here has more the character of an "explosion", and it is technically impossible to transfer the heat developed during the required specific loadings of the focus to running water so rapidly.

It is however possible to obtain an increase in the specific loading by allowing the anode to rotate during the exposure time. In that case fresh, still cold parts of the anode pass successively under the beam of electrons, and each point is loaded for only a fraction of the exposure time. This idea is already quite old (Breton 1898—1899); it was however only realized in a practical form by Bouwers in 1929 [5].

### Improvement attainable with rotating anode

We shall now examine what improvement of the specific loading can be theoretically and practically attained with a rotating anode. For times $t < 0.04$ sec (in the range of temperatures with which we are concerned) the rise in temperature $T—T_0$ at the surface of a loaded anode is given approximately by

$$T - T_0 = AW\sqrt{t} \quad . \; . \; . \; . \; . \quad (2)$$

$W$ is here the specific loading, and $A$ is a constant depending upon the heat conductivity and specific heat of the anode material. Instead of allowing the anode to turn under the electron beam we may imagine for the sake of simplicity that the focus is displaced over a stationary anode, which amounts to the same thing. If during the exposure the focus of width $f$ moves over a distance $m.f$ the time during which a given point of the anode is loaded becomes $m$ times as small. According to (2) the increase in temperature at the surface then becomes $\sqrt{m}$ times as small, or, with a specific loading $\sqrt{m}$ times as great, the original increase in temperature is again obtained. This is illustrated in *fig. 2*. With a stationary anode the temperature at the focus varies during loading according to parabola *1* (see equation (2)). Line *2* represents the variation of the temperature with a rotating anode under the same load and with a speed of rotation such that the anode is displaced a distance of 16 $f$ during the exposure time. At a specific loading $\sqrt{16} = 4$ times as great (line *4*) the same maximum increase in temperature is then obtained as with the stationary anode. If in general the displacement of the anode during loading is $p^2$ times the width of the focus, the permissible loading is improved by a factor $p$. Now the following relation holds:

$$p^2 f = 2\pi r n t,$$

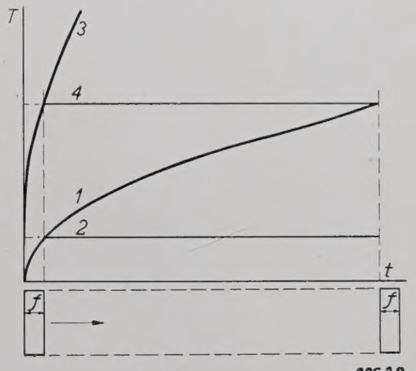

Fig. 2. Variation of the temperature $T$ at the focus during loading. The initial temperature $T_0$ is set equal to zero for the sake of simplicity. Curves *1* and *3* with stationary anode, curves *2* and *4* with rotating anode. The specific loading in curves *3* and *4* is four times as great as in curves *1* and *2*.

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[4] J. E. de Graaf and W. J. Oosterkamp Philips techn. Rev. **3**, 263, 1938.

[5] A. Bouwers, Kongressheft Fortschr. Röntgenstr. **20**, 103, 1929.

where $r$ is the distance from the middle of the focus to the axis of the anode, $n$ the number of revolutions and $t$ the loading time. The theoretically attainable improvement factor $p$ of the specific loading upon transition from stationary to rotating anode therefore becomes:

$$p = \sqrt{2\pi r n t / f} \quad \cdots\cdots \quad (3)$$

From the derivation of this formula it may be seen that it is only valid for a limited range of loading times $t$. If $t$ is so small that $mf \leqq f$, *i.e.* if the anode is displaced by less than one focus width during the loading, no improvement is obtained by the rotation of the anode: a strip of the focus which may be wider or narrower is in the latter case always loaded during the time $t$ and the permissible loading is limited by this critical strip, which amounts to the same thing as if the whole focus were loaded during the whole time $t$ (stationary anode). For shorter loading times than those at which $mf = 2\pi r n t = f$, *i.e.* for $t \leqq f/2\pi r n$, therefore, formula (3) is not valid, but $p$ is a constant equal to unity.

On the other hand formula (3), as well as (2) from which it is derived, holds only for exposure times $t < 0.004$ sec. For longer times the rate of increase in temperature with a stationary anode is less than proportional to $\sqrt{t}$; therefore, under otherwise similar conditions, the improvement factor increases less and less rapidly with increasing exposure time, and would finally approach a definite maximum value. Furthermore, however, with longer exposure times, *i.e.* when $t > 1/n$, one spot on the rotating anode passes under the electron beam more than once during the whole loading. The second time that a spot is loaded it will have retained a certain temperature increase from the first time, and this will be even greater the following times; therefore the loading may not be increased by the theoretical factor $p$, but only by a smaller factor if the same maximum focus temperature is to be reached. There is therefore even a decrease in the improvement factor $p$ with increasing exposure time $t$. For extremely long exposure times $p$ is independent of the time $t$, it is then determined by the material, the form and cooling of the anode.

In the practical construction of "Rotalix" tubes, which we shall describe later, $r = 2$ cm, $n = 2\,900$ rev/min., $f = 1.3$ mm. From equation (3) it then follows that specific loading with the rotating anode for $t = 0.04$ sec could be more than 13 times as great as with a stationary anode. With $n = 2\,900$ rev/min. during one exposure of 0.04 sec about two revolutions occur, so that the actual improvement factor is smaller (the temperature increase retained after one revolution is in the practical case about 60°).

Moreover in the case of the anode of the "Rotalix" tube for practical reasons (see page 301) one must calculate with a basic temperature of $Tg = 450°$C instead of the temperature assumed up to now of 0°C. This also makes the practically attainable improvement factor smaller. It amounts to about 8 or 9. In *fig. 3* the measured improvement factor is plotted as a function of the time. The lower limit of validity of formula (3) lies in our case at $t = 0.0002$ sec. The theoretical variation of $p$ according to (3) is indicated by a dotted line.

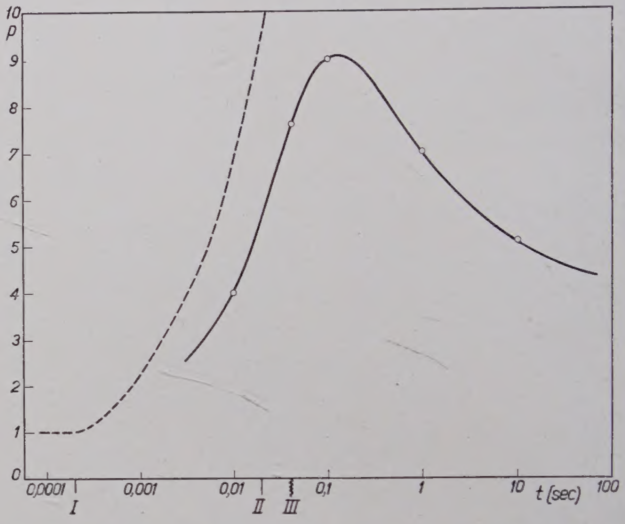

Fig. 3. Variation of the improvement factor $p$ of the specific loading as a function of the exposure time $t$ upon transition from stationary to rotating anode ($t$ is plotted logarithmically). Width of focus $f = 1.3$ mm, radius of anode $r = 2$ cm, number of revolutions $n = 2\,900$ per min. At $t < 0.002$ sec (left of *I*) no improvement is obtained ($p = 1$). For $0.0002 < t < 0.02$ sec. $p$ varies theoretically according to formula (3) (dotted line). Due to the higher basic temperature of the anode after continued use the practical value of $p$ is less than the theoretical one (continuous line). At $t > 0.02$ sec (right of *II*) a single spot on the anode passes more than once under the electron beam. Finally at $t > 0.04$ sec (right of *III*) the focus temperature with stationary anode increases at a rate less than proportional to $\sqrt{t}$. For these two reasons the improvement factor falls with higher values of $t$, and approaches a value independent of $t$.

An attempt might be made to increase $p$ still further by giving the anode a greater diameter ($2r$) and a higher speed of revolution ($n$). This is possible technically. Such an improvement however would at present still serve no useful purpose. With the increase of the specific focus loading it is only in the geometrical and kinematic lack of sharpness of the picture that a decrease is obtained. There is still a third source of lack of sharpness which is inherent in the photographic material used (namely the fluorescent intensifying screens). As long as this lack of sharpness remains unchanged it is useless to decrease the other contributions to the total lack of sharpness below a certain limit. This limit has been almost reached with the photographic material at present available.

In *fig. 4* the improvement obtained in the specific loading is illustrated in a different way: a focus of a tube with a stationary anode ($a$) and the equivalent focus with a rotating anode ($b$) are shown next to each other, both to be loaded with 21 kW during 0.1 sec.

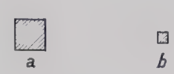

Fig. 4. Focus (in projection, see below) of a tube with stationary ($a$) and with rotating ($b$) anode, both loaded with 21 kW during 0.1 sec.

**Form of the focus**

In the article quoted in footnote [4]) it has already been explained in detail that, due to the nonvalidity of Lambert's law in X-ray emission, the focus exhibits a considerably greater brightness in an oblique direction of observation than in a normal direction. Use has been made of this fact in "Rotalix" tubes also. These tubes have a so-called line focus with the dimensions 1.3 · 5.2 mm and the central ray of the effective cone makes an angle of 15° with the surface of the anode. In this projection the focus appears as a square 1.3 · 1.3 mm, and would then, as far as the total X-ray intensity in this direction is concerned, be equivalent to a circular focus observed normally of almost 3.0 mm diameter with a stationary anode. The much smaller apparent dimensions of the line focus are an important advantage from the point of view of sharpness of the picture. For a tube with a rotating anode, however, the line focus offers an additional advantage. According to equation (3) upon rotation the improvement factor $p$ is proportional to $\sqrt{n/f}$, *i.e.* a given number of revolutions accomplishes, for the line focus of $f = 1.3$ mm, as much as double the number of revolutions would accomplish for the circular focus of width (diameter) $f = 3.0$ mm.

Finally in *table I* the permissible loading is given of a "Rotalix" tube with a line focus of 1.3 mm width, for several loading times (with direct voltage).

**Table I**

| Loading time in seconds | Permissible loading in kW |
|---|---|
| 0.01 | 24.5 |
| 0.04 | 23 |
| 0.1 | 20.5 |
| 1.0 | 11 |
| 10.0 | 6 |

**Construction of "Rotalix" tube**

In *fig. 5* the construction of a "Rotalix" tube is given diagrammatically. For the general construction (small discharge space surrounded by metal, window for the emission of the X-rays, screening from the undesired X-rays by lead, protection against high voltage by earthed metal jacket) we may refer to the X-ray tube previously described for the investigation of crystal structure [4]), which exhibits the same characteristics. The anode $A$ can rotate about the axis $C$. The driving force is obtained as in an induction motor: the windings on the stator $S$ are supplied with polyphase current, the copper anode itself forms the rotor turning in a vacuum, upon which a couple acts due to the induced eddy current. The iron field ring $E$ serves to cause as many lines of force as possible to pass through the copper. For the same reason the distance between stator and anode is made as small as possible. Since the stator is earthed and the anode is under high tension, this distance is limited by the distance necessary to avoid break-down. The high tension is supplied to the anode *via* a brush contact.

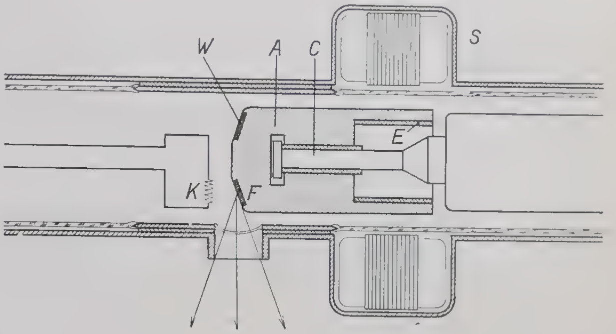

Fig. 5. Construction of a "Rotalix" tube (diagrammatic). The discharge space between the cathode $K$ and the anode $A$ is completely surrounded by metal. The cathode is mounted excentrically in the tube and constructed in such a way that a line focus $F$ occurs along a line of revolution of the conical front surface of the anode, upon which a layer of tungsten $W$ is applied. The anode turns about the axis $C$. It is driven in the manner of the armature of an induction motor by a polyphase current in the stator windings $S$. The iron field ring $E$ causes as many lines of force as possible to pass through the copper of the anode.

The problem of lubrication of the bearings of the rotating anode in the evacuated tube is solved in the case of "Rotalix" tubes by the use of a special grease (a high distillation product of petroleum) in combination with ordinary ball bearings. The vapour pressure of this grease is only $10^{-6}$ mm at 150°C.

Special care is taken that the bearings, which must be well outgassed before mounting, do not become too warm during running, so that the vapour pressure of the lubricant remains low during use. Moreover, in the "Rotalix" tube as well as in all "Metalix" tubes a getter is employed [6]), which is introduced in such a position that it can easily be reached by gases and vapour from the grease which are freed in the bearings. Thanks to these precautions the vacuum in the tube is not impaired by the presence of the lubricant.

### Construction of the anode

For several reasons the most suitable material for the anode of an X-ray tube is tungsten. This is especially true of tubes for diagnosis which are particularly constructed for X-ray photography of moving objects, in which, as we have seen, high permissible loading during a short time is essential. The intensity of the X-radiation is proportional to the atomic number which is very high in the case of tungsten, namely 74. The melting point of tungsten is higher than that of any other suitable metal; (approximately 3 400°C). The vapour pressure is small so that the material may be heated to more than 2 500°C for a short time without causing the vapour pressure in the X-ray tube to rise unduly. The heat conductivity is 40 per cent of that of copper, and therefore quite satisfactory. Considering that for the parts of the anode lying behind the focus the high melting point, the high emission of X-radiation, etc. of tungsten are no longer important factors, and, that there only is the best possible heat conduction to the back (perpendicular to the surface of the focus) desired, copper can be used to advantage for these parts. The anode consists of a massive copper block upon which the focus is applied in the form of a thin layer of tungsten. The surface of the focus reaches temperatures of about 2 500°C during the very brief loading times; the temperature of the boundary surface tungsten-copper may however not exceed 1 000°C, since the melting point of copper is about 1 080°C. At a given specific loading therefore the optimum thickness of the tungsten layer depends upon the loading time. With loading times of the order of 1 sec the most suitable thickness is about 1.5 mm, for shorter times it is considerably smaller, for instance only about 0.3 mm with a loading time of 0.04 sec.

It is obvious that the anode material is put under severe strain during loading. In the tungsten layer within a distance of 0.3 mm between front and back there is a temperature difference of about 1 500°C, and the front surface reaches temperatures of more than 250°C. In addition there is the alternate heating and cooling of the material with resulting buckling and shrinking. A tungsten layer in the form of a plate proves unable to withstand all this for a long time. Therefore in "Rotalix" tubes the tungsten layer on the anode is composed of spirally-wound tungsten ribbon (with the axis of the anode as axis of winding) 0.12 mm. thick and 0.3 mm wide. The layer is then 0.3 mm thick. The copper of the anode must also be reinforced to prevent the occurrence of cracks. This is done by means of so-called tungsten wool consisting of a bunch of tungsten wires (each wire 0.1 mm thick, 5 wires per sq.mm.), with which the individual crystals of copper are anchored, as it were, during the casting of the copper block of the anode.

### Cooling of the anode

The increase in temperature of the massive anode block is fairly slight during one exposure. It is therefore possible to make a number of successive photographs without the anode as a whole becoming very much warmer. In the early models of "Rotalix" tubes therefore no special provision was made for cooling the anode. It then took some time before a heated anode was again quite cold, since convection and heat conduction have no effect in the evacuated tube, and the anode could lose accumulated heat only by radiation. The use to which the tubes were put made a change necessary here. Contrary to the original intention the "Rotalix" tube was used not only for taking photographs of moving organs, but also of practically stationary objects; at present it is even used for fluoroscope examinations (in this case the anode need not even turn, since it can take up such small loads when stationary). In order to make the tube also suitable for such continuous use the anode had to be cooled.

*Fig. 6* gives a diagrammatic representation of the anode of a "Rotalix" tube with a cooling system [7]). As already mentioned, dissipation of heat can only be obtained by radiation. Therefore

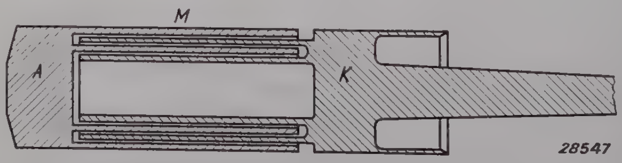

Fig. 6. The cooling of the anode $A$ rotating in a vacuum, which is necessary for continuous use of the tube, takes place by radiation of the blackened cylindrical shells $M$ upon similar shells of the stationary support $K$.

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[6]) J. H. van der Tuuk, Ned. T. Natur. **3**, 129, 1936.

[7]) A. Bouwers, Fortschr. Röntgenstr. **48**, 232, 1933.

the radiation is made as great as possible. Blackened cylindrical shells $M$ projecting from the rotating anode $A$ radiate the heat on similarly blackened shells of the stationary support $K$. The amount of heat transferred per second then amounts to the following, according to the Stefan-Boltzmann law

$$Q = c \cdot O \cdot \sigma \, (T_A^4 - T_K^4) \quad \cdot \; \cdot \; \cdot \; \cdot \quad (4)$$

where $c$ is the heat transfer coefficient between the shells, $O$ the total surface of the shells $M$, $\sigma$ the radiation constant ($5.3 \cdot 10^{-12}$ watt cm$^{-2}$ degree$^{-4}$), and $T_A$ and $T_K$ are the absolute temperatures of the anode and support respectively. The coefficient $c$ for cylindrical surfaces is approximately $z/\,(2 - z)$ where $z$ is the blackening coefficient. The surface of the shells $M$ is for instance 400 sq.cm, and at an easily attainable value of the blackening cofficient $z$ of 0.7 the coefficient of heat transfer $c = 0.54$. It can be estimated that the anode as a whole reaches a basic temperature of about 450°C, while the support $K$ which can give off its heat to the air around the tube reaches a temperature of about 200° with intensive use of the tube [8]). With these values it can be calculated from (4) that an amount of energy of more than 200 W can be dissipated continuously through the anode, this is a load which is very seldom necessary for several consecutive hours in X-ray diagnosis. The support which receives the heat by radiation from the anode must in its turn get rid of it, and the necessary electrical insulation forms an obstacle to this process. The simplest solution is sketched in *fig. 7*. A blackened cooling bulb $B$ is mounted on the support, and by convection through the air, and partly also by radiation, it gives off its heat to the earthed container of the whole tube.

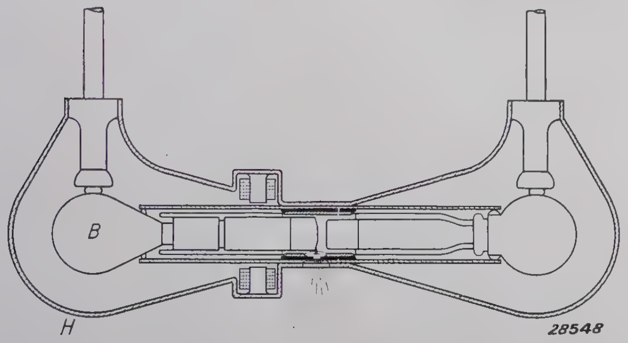

Fig. 7. For the cooling of the support $K$ in fig. 6 a cooling bulb $B$ is mounted on it, which gives off its heat by convection to the surrounding air and by radiation to the earthed container $H$ of the tube.

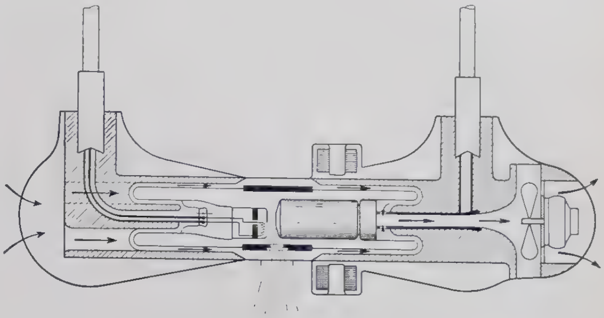

Fig. 8. The support in fig. 6 and the whole tube may be cooled by means of a fan by air circulation. This makes it possible, especially when the insulation between tube and earthed container is obtained with the help of high-tension "Philite" (instead of air), to make the dimensions of the tube considerably smaller.

Because of the necessary large surface of the cooling bulb the tube then becomes fairly large. This can be avoided by cooling the support and tube directly by air circulation, by means of a fan. The reduction in the dimensions of the tube is then limited only by the necessary insulation distance between the tube proper and its container. If this space is filled with high tension "Philite", which has a much higher break-down potential than air, the whole tube can be still further reduced in size. In *fig. 8* is shown a cross section diagram of a tube insulated in this way with fan cooling. *Fig. 9* gives photographs of two "Rotalix" tubes, the lower with cooling bulbs according to fig. 7 and the upper with fan cooling according to fig. 8.

Because of the great mass of the anode (1200 g) the "Rotalix" tube is also specially suitable for a particular application, namely X-ray cinematog-

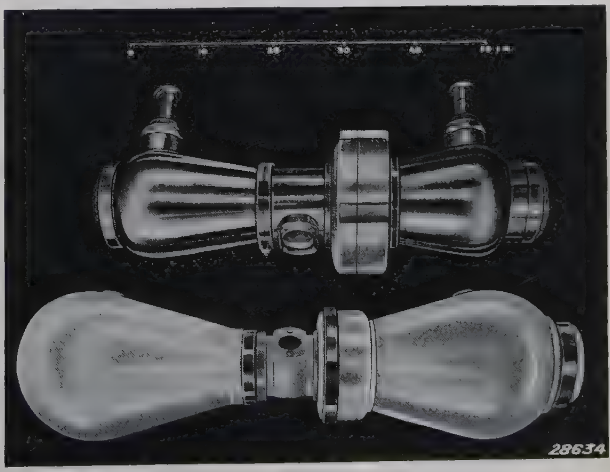

Fig. 9. Two "Rotalix" tubes projected against high tension and X-radiation: the lower with cooling bulb according to fig. 7, the upper with fan cooling according to fig. 8.

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[8]) Since the radiation increases sharply with the temperature, it seems tempting for constructional reasons to choose the basic temperature $T_A$ of the anode mass higher, in order to be able to use a smaller surface. A higher basic temperature however means, as we have seen above, a lower specific loading, while the problem is just to make this as high as possible.

raphy [9]). In the latter 12 exposures per sec. are made for 20 sec. for example. The X-ray tube is loaded for 20 consecutive seconds with more than 5 kW; the total amount of heat supplied thus amounts to more than 100 kW sec. ≈ 25000 cal. This heat supplied, in a mass of 1200 g and a specific heat of copper of about 0.08, caused a rise in temperature of the whole anode block of about 250°C. The cooling of the anode by radiation makes it possible to repeat such extremely heavy loadings at fairly short intervals.

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[9] van de Maele, J. belge Radol. Nr. 137, 1935.

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# THE DIFFRACTION OF LIGHT BY SOUND FILM

by J. F. SCHOUTEN

534.44 : 535.42 : 778.534.45

The light diffraction phenomena which are obtained with a strip of sound film may used to analyse the sound. If a pure sinusoidal oscillation is registered on a film according to the intensity system, the grating so obtained produces, in addition to the non-diffracted rays, only first order spectra. If the oscillation contains higher harmonics, diffraction spectra of higher orders also occur. The intensity of each order is determined by the amplitude of the corresponding harmonic. If the sound is registered according to the amplitude system the diffraction phenomena become more complicated. A two-dimensional diffraction pattern with two axes of symmetry is obtained. The distribution of intensity on the horizontal axis of symmetry, which is parallel to the axis of symmetry of the sound track on the film, corresponds to the diffraction spectrum of the film registered according to the intensity system, and may therefore, like that spectrum, be used to analyse the sound. In this article several examples are given: sinusoidal tone, tone with second harmonic, tone with third harmonic, transmission grating, tone with frequency modulation. Finally the frequency characteristic of an amplifier is determined according to the above method.

## Introduction

In general light is composed of radiation of various wave lengths. An ordinary electric lamp, for example, emits all wave lengths to which the eye is sensitive to a certain degree depending uniformly on the wave length. This can best be seen by observing the light through a spectroscope. In such an instrument the kinds of light of different wave length are projected next to each other in a plane, so that an immediate impression is obtained of the spectral composition of the light.

If for example we observe sunlight through a spectroscope we see dark lines, the Frauenhofer lines, on a continuous spectrum. This means that those wave lengths are present in sunlight in only a slight amount. If, on the other hand, we consider a gas-discharge lamp, for example a sodium, mercury or a neon lamp, through a spectroscope, we observe, instead of a continuous spectrum, only a few narrow coloured lines on a dark background. This means that this light is composed of several definite wave length regions.

The presence and the position of these regions could also be determined roughly by observing the light source through coloured filters. Such filters transmit certain regions of the spectrum and absorb the rest of the light. We can now find out through which filters the light source is visible or invisible. The spectroscope, however, and that is is its fundamental advantage over coloured filters, offers the possibility of obtaining an immediate impression of the number, position, intensity and extensiveness of these regions *i.e.* of the spectral composition of the light.

In the case of sound we encounter the same problems as with other waves. Every sound may be considered to be composed of pure sinusoidal oscillations of different frequencies, each of which by itself causes a sound impression of different pitch, and which together give the impression of a certain tone.

Among the sounds, with which we are practically concerned, the frequencies of which they are composed do not usually have such continuously distributed values as is the case for example with light. From the nature of the origin of the tones, the motion of the sources of sound is repeated periodically. This is seen most clearly when sound is registered with a cathode ray oscillograph. With this instrument a graphic representation is obtained of the displacement of the vibrating air particles as a function of time. If the period of the time axis voltage is made sufficiently long, one then sees along the axis a periodically repeated oscillation picture which has a certain shape, sinusoidal, square-topped or saw-toothed.

In the case of any purely periodic oscillation, it can be shown that it may be built up of a sinusoidal basic tone and sinusoidal overtones of double or triple frequencies, etc. The sound spectrum thus consists here of a number of discrete frequencies which are integral multiples of the basic frequency. The sound impression of such a tone is determined by the relative strengths of the basic tone and the various overtones.

It will have been noticed that in the analysis of light we always spoke of the wave lengths which compose it, and when speaking of sound, of the frequencies of which it is composed. The result is the same, because wave length and frequency can be expressed in terms of each other by means of the velocity of propagation. The difference in terms used is chiefly due to the fact that our elementary idea of the spectral composition of light is supported by the diffraction phenomena in which wave length is a decisive factor, while the spectral composition of sound is known to us mainly from resonance phenomena in which frequency is the decisive factor. Considering the fundamental analogy between the composition of light and that of sound, the obvious question arises as to the possibility of obtaining a direct spectrographic analysis of sound similar to that of light. Instruments actually exist for this purpose, but due to their complex construction they are only seldom used. The problem has therefore been solved by calculating from recorded oscillograms the sinusoidal components of which they are composed with the help of Fourier analysis. This is, however, generally a fairly elaborate method.

Nevertheless the question of the spectral composition of sounds is often very important. This is true of the study of the human voice and of the sounds produced by musical instruments. It is especially true in technical acoustics for the study of the distortion which may be caused by acoustic and electrical apparatus. This distortion is manifested in the fact that with a pure sinusoidal input signal of a given frequency, overtones also occur in the output signal. The problem is solved in the investigation of these overtones by going over the whole region with an electrical filter of adjustable frequency. How much more satisfactory it would be to be able to obtain an immediate idea of the spectral composition of the sound.

According to an original idea of Brown ¹) immediate insight into the spectral composition of sound can be obtained if the temporal periodicity of the sound is transformed into a special periodicity by recording it on a sound film. The latter can then be used as an optical diffraction grating.

We shall develop this idea further in this article, with special emphasis on the close analogy between the sound spectrum of a composite sound and the diffraction spectrum of an optical grating, an analogy which is expressed in the possibility of mathematical analysis into Fourier series.

## The diffraction spectrum of a transmission grating

Sound film consists of a black strip in which a transparant strip has been left free. We distinguish between two systems: the intensity system and the amplitude system. In the intensity system the width of the transparent strip is kept constant and its transmissibility is varied proportionally to the amplitude of the sound recorded. In the amplitude system the transmissibility of the strip is kept constant, but its width varies proportionally to the amplitude of the sound recorded. If a narrow beam of light is projected on the film perpendicular to the direction of length of the film, and if the film is moved in the direction of its length, the amount of light transmitted will in both cases vary proportionally to the amplitude of the sound registered on the film, and may therefore be transformed into the original sound.

In order to understand the behaviour of such a section of sound film as a diffraction grating, we must refer to the theory of optical gratings.

We assume (*fig. 1*) the plane of the section of film to be vertical and the direction of its length to be horizontal. Then (see also fig. 4) we suppose that on this strip of film there are an infinite number of very fine equidistant lines of equal height which transmit light. We shall now investigate the spectrum of this transmission grating. A parallel beam of light falls horizontally on the film. The light may be obtained from a small source at a great distance. The light which passes through the slits (*fig. 2*) will be diffracted in a horizontal direction ²). The direct rays will all be in the same phase and therefore reinforce each other. We can also find a certain angle of diffraction $\alpha$ at which the ray diffracted from one slit is exactly one wave length ahead or behind in phase to that from the two adjacent

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¹) D. Brown, Nature, **140**, 1099, 1937.

²) We shall in this article concern ourselves only with the diffraction in the horizontal direction and shall not discuss the diffraction in the vertical direction.

slits. For that angle the rays coming from the different slits will again be in phase and therefore also reinforce each other.

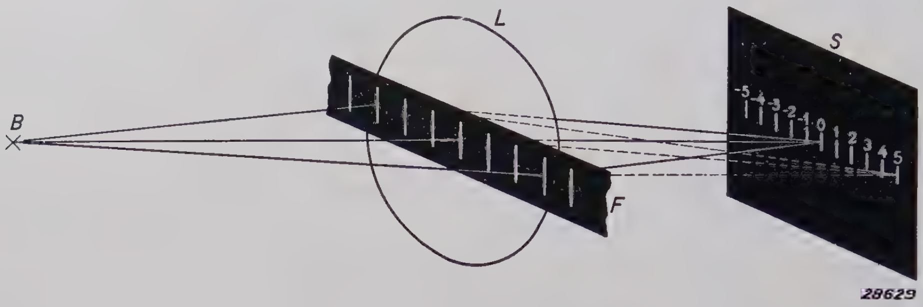

Fig. 1. Experimental arrangement for obtaining diffraction spectra. A point source of light $B$ illuminates the strip of film $F$ with practically parallel monochromatic light. On the screen $S$ at the focus of lens $L$ the diffraction spectrum may be seen. The strip of film $F$ has a number of very narrow equidistant light transmitting slits. The spectrum now consists of a number of equidistant vertical lines.

The same is true for every angle of diffraction at which two adjacent rays have a phase difference of a whole number of wave lengths. At certain angles therefore maxima will appear in the intensity transmitted. The condition for the appearance of these maxima is the following:

$$\sin \alpha_n = \frac{n\lambda}{l}, \quad n = 0, \pm 1, \pm 2, \pm 3, \dots \quad (1)$$

$\lambda$ is here the wave length of the light used and $l$ the distance between the slits.

If a positive lens is placed behind the film, a point image of the source would be formed at the focus of the lens if the film were not there. Due to the presence of the film there is now a vertical line instead of the point, due to the refraction of light in a vertical direction. To the left and right occur a number of equidistant lines of equal intensity which we shall call the first, second, third, etc. orders according to the customary usage in spectroscopy (fig. 4).

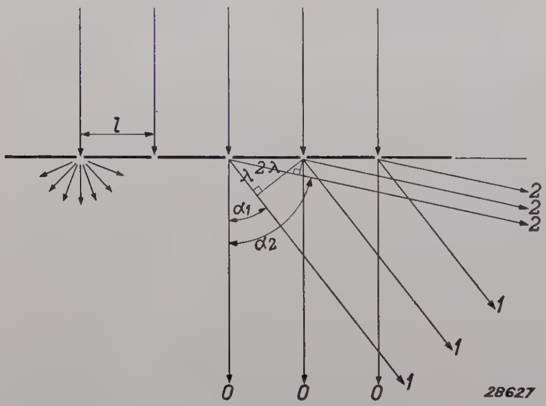

Fig. 2. The production of a diffraction pattern by a transmission grating.

Left: The light rays passing through the slits are refracted in all directions in a horizontal plane.

Right: The rays in a given direction coming from the different slits interfere with each other. The result is that the resulting intensity is equal to zero except for those directions in which two neighbouring rays have a phase difference equal to a whole number of wave lengths. In the figure are given the rays of the zero order (no phase difference), the first order (phase difference $\lambda$), and the second order (phase difference $2\lambda$).

A few words must be said about the order of magnitude of the angles of diffraction which prevail. With optical gratings $l$ is about $2\mu$. At a wave length of $0.6\mu$ for the first order $\sin \alpha = 0.3$ and $\alpha$ therefore about 18 degrees. With sound film, at 300 cycles the length of one cycle on the film, $l$, is 1 mm. Therefore $\sin \alpha = 0.006$ and $\alpha = 0.006$ radians $= 2$ minutes. We may therefore conveniently substitute $\alpha$ for $\sin \alpha$ and write

$$\alpha_n = \frac{n\lambda}{l}, \quad n = 0, \pm 1, \pm 2, \pm 3, \dots \quad (2)$$

Except at the maxima the intensity of the diffraction spectrum must always be zero. For every angle which does not satisfy condition (2), in the case of every slit of the infinitely long grating there is always another slit such that the two rays are exactly in opposite phase and thus cancel each other.

*The spectrum of an infinitely long ideal transmission grating contains all the higher orders in equal intensity.*

## The diffraction spectrum of a sinusoidal intensity grating

Let us now consider a strip of sound film on which a pure sine is recorded by the intensity system. The width of the strip is constant and the transmissibility as a function of the place $x$ on the film is variable. Let the transmissibility $D$ be given by

$$D = a + b \cos \frac{2\pi x}{l}, \quad \dots \quad (3)$$

*i.e.*, by a constant component $a$ and a sinusoidal variable component with amplitude $b$ and period $l$.

The equidistant points on this "grating", $x = 0$, $x = \pm 1$, $x = \pm 2$, etc. all have the same transmissibility. Together they may be considered analogous to the transmission grating described in the previous section. In the focal plane this grating gives the following light oscillation for all orders

$$(a + b) \sin 2 \pi \nu t,$$

where $\nu$ is the frequency of the light used (the amplitude is thus set equal to the transmissibility). In the same way the points $x$, $x \pm l$, $x \pm 2l$, etc. all have the same transmissibility $a + b \cos 2 \pi x/l$. They may therefore also be considered as a transmission grating which, however, is shifted a distance $x$ with respect to the first grating. The rays from this latter at an angle of $\alpha$, cover a distance $\alpha x$, and are therefore a phase angle $2 \pi \alpha x/\lambda$, ahead of the first ones. They thus contribute to the light oscillations the amount:

$$(a + b \cos 2\pi x/l) \sin (2 \pi \nu t + 2 \pi \alpha x/\lambda),$$

or substituting the value of $\alpha$ in (2):

$$(a + b \cos 2\pi x/l) \sin (2 \pi \nu t + 2 \pi n x/l).$$

The total light oscillation $M_n$ which is produced by the whole grating in the $n^{th}$ order is

$$M_n = \int_0^l \left(a + b \cos \frac{2\pi x}{l}\right) \sin \left(2 \pi \nu t + \frac{2 \pi n x}{l}\right) dx \quad \cdot \quad (4)$$

When we set $2 \pi x/l$ equal to $\varphi$, this gives, except for a constant factor, the following,

$$M_n = \int_0^{2\pi} (a + b \cos \varphi) \sin (2 \pi \nu t + n \varphi)\, d\varphi =$$

$$= a \int_0^{2\pi} \sin (2 \pi \nu t + n \varphi)\, d\varphi + b \int_0^{2\pi} \cos \varphi \cdot \sin (2 \pi \nu t + n \varphi)\, d\varphi. \quad (5)$$

The first integral of (5) is zero for all values of $n$ except $n = 0$, which gives

$$M_0 = 2 \pi a \sin 2 \pi \nu t \quad \cdot \cdot \cdot \cdot \cdot \quad (6)$$

The second integral of (5) may be written as follows:

$$\frac{b}{2} \int_0^{2\pi} \sin [2 \pi \nu t + (n - 1) \varphi]\, d\varphi +$$

$$+ \frac{b}{2} \int_0^{2\pi} \sin [2 \pi \nu t + (n + 1) \varphi]\, d\varphi.$$

The first integral of this expression is always equal to zero except for $n = +1$, when it gives

$$M_{+1} = \pi b \cdot \sin 2 \pi \nu t, \quad \cdot \cdot \cdot \cdot \cdot \quad (7)$$

while the second integral is always equal to zero except when $n = -1$, when it gives

$$M_{-1} = \pi b \cdot \sin 2 \pi \nu t \quad \cdot \cdot \cdot \cdot \cdot \quad (8)$$

Therefore if the signal $a + b \cos \varphi$ is registered on the film, we see in the zero order of the spectrum a light oscillation whose amplitude is proportional to the average value $a$ of the signal, and in the first order to the right and left ($n = +1$ and $-1$) an oscillation whose amplitude is proportional to the amplitude $b$ of the sinusoidal variations, while all higher orders are missing. The intensity of the light here becomes proportional to the squares of $a$ and $b$ respectively.

It is easy to show that when the registered sound does not consist of one, but of several pure tones, several lines will also occur in the diffraction spectrum, whose positions will be determined by the frequency, and whose intensity by the amplitude of the tones in question.

*The diffraction spectrum of a strip of sound film recorded by the intensity system gives exactly the Fourier series of the sound recorded on the film.*

This is substantially a well-known proposition of the theory of optical gratings, which now, however, may be observed from a different point of view through its interpretation for the study of sound. With optical gratings our problem is to deduce the spectral analysis of light from the spectrum. The characteristics of the diffraction grating in that case interest us only in so far as they affect the greatest attainable accuracy. In the use of sound film as optical grating our problem on the other hand is to deduce from the diffraction spectrum the characteristics of the grating. In this latter case it is the spectral composition of the light which may appear as a disturbing factor, since according to (2) the position of the maxima is a function of the wave length used. Therefore all records are made with monochromatic light (the green mercury line $\lambda = 5461$ Å).

With a sound film recorded by the amplitude system, diffraction phenomena occur which are much more complicated than with a sound film recorded by the intensity system ³).

In most cases a two-dimensional symmetrical pattern is obtained as shown in *fig. 3* for different sound tracks. Even when a pure sine is recorded in the strip, all the higher orders appear in the spectrum. On the horizontal axis of symmetry, however, the same proposition is valid as that deduced for the film recorded by the intensity system.

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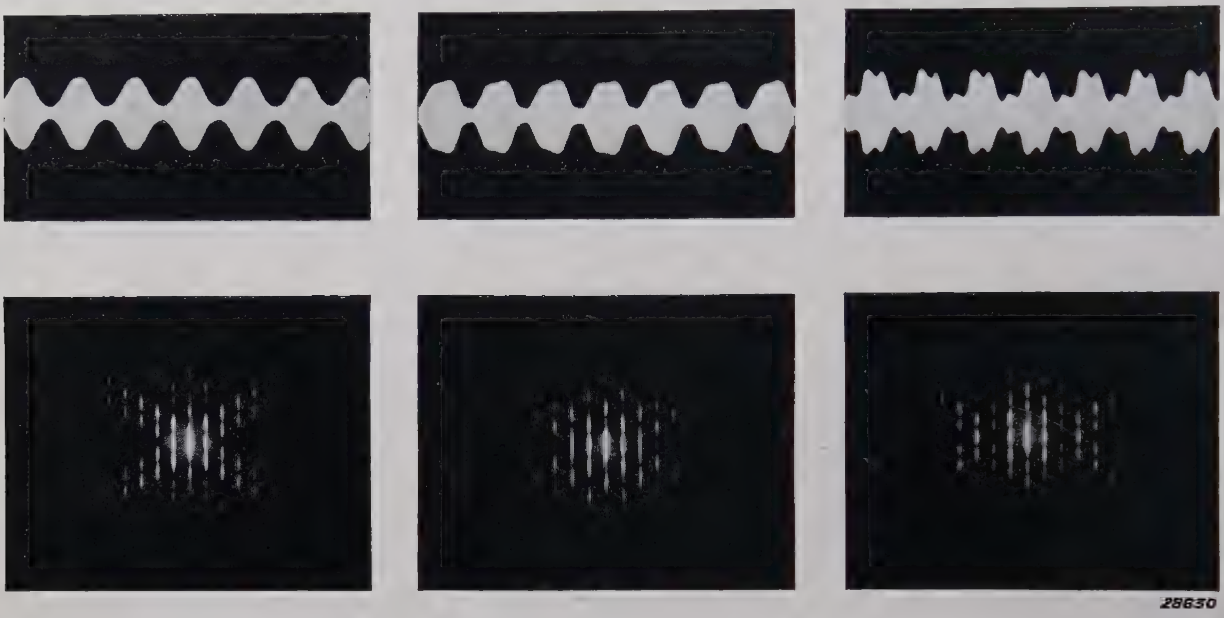
³) J. F. Schouten, Nature **141**, 914, 1938.

In fig. 3*a* a tenfold enlargement is given of a practically pure sinusoidal sound track and of the spectrum obtained from it. On the horizontal axis, in addition to the zero and first orders, only a very weak third order is visible. Fig. 3*b* refers to a sound track with strong second and weak third harmonics, and fig. 3*c* to a sound track with practically only a third harmonic.



a b c

Fig. 3. Harmonic analysis of sound registered on a strip of film by means of diffraction patterns.
Above: the strip of film used (tenfold enlargement).
Below: the diffraction pattern.
a) Practically sinusoidal oscillation. On the horizontal axis of symmetry of the diffraction pattern, except for a weak third order, only the zero and first orders appear.
b) Basic tone with strong second and weak third harmonics.
c) Basic tone with strong third harmonic. The second harmonic is missing.

In this way it is possible to analyse the spectrum of periodic phenomena. In the following we shall discuss several characteristic examples, and conclude with a special application: the determination of the frequency characteristic of a system.

## The spectrum of a periodically repeated impulse

We deduced the proposition formulated above from the simple spectrum of a transmission grating. We may now, conversely, carry out experimentally the analysis into Fourier series of the transmission grating (in acoustics: a periodically repeated impulse) with the help of this proposition. As previously mentioned, all orders have the same intensity in the diffraction spectrum of a transmission grating. In the Fourier analysis of a periodically repeated impulse, therefore, all overtones occur with equal amplitude. As may be seen from *fig. 4*, however, the higher orders become gradually weaker when the experiment is actually carried out. The explanation of this is simple from the point of view of Fourier analysis. The slits are of course not infinitesimally narrow, but have a definite, though small width. This is manifested in Fourier analysis by the fact that the strength of the overtones gradually decreases with increasing order, passes through zero and then varies periodically. The first decrease is shown clearly in fig. 4.

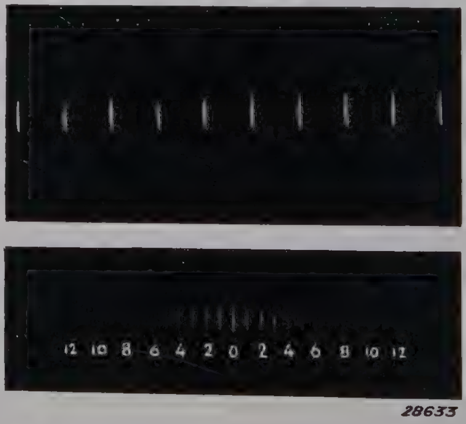


Fig. 4. The spectrum of a transmission grating (periodically repeated impulse).
Above: tenfold enlargement of the strip of film used. Frequency 250 c/s.
Below: the spectrum of the transmission grating. All orders must appear in equal strength. The gradual decrease in intensity of the higher orders is due to the finite width of the slits on the film.

### The spectrum of a finite train of waves

In the derivation of the spectra we have assumed until now that the strip of film was infinitely long. In practice the strip will always have a finite length, so that the spectrum always refers to a "wave train" of, for instance, several centimetres. How will this fact be manifested in the spectrum? As an example let us consider a finite portion of a pure sine. The Fourier analysis of an infinitely long sine gives us a discrete frequency, namely that of the sine itself. If, however, the oscillations are interrupted at a definite point the Fourier analysis of this function, which is actually no longer purely periodic, does not give a single frequency, but a frequency band, flanked by weaker side bands. It can be proved that the width of the central band in periods is equal to twice the reciprocal of the time interval in which the wave train passes.

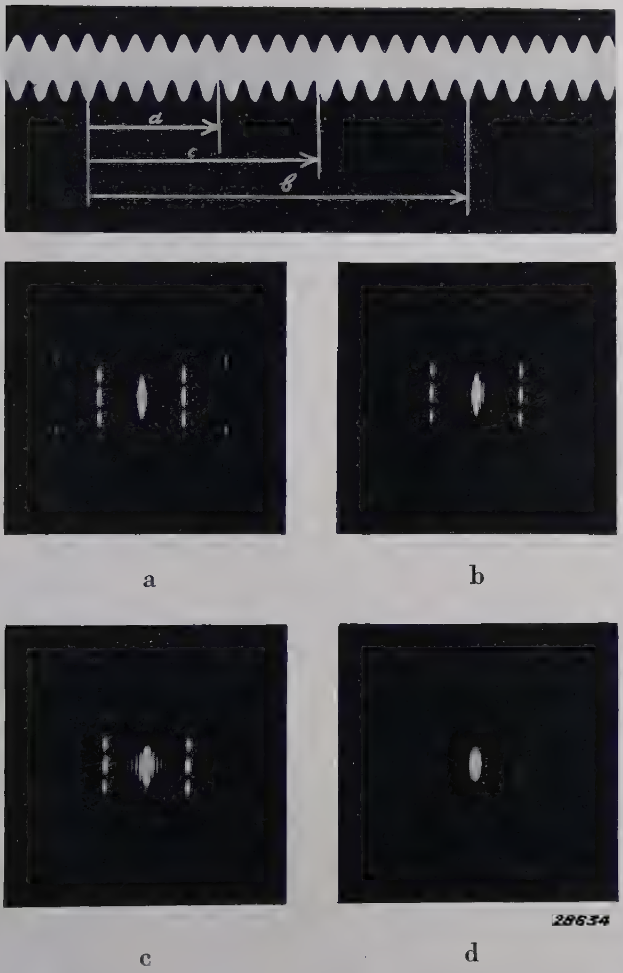


Fig. 5. Influence of the length of the strip of film on the width of the diffraction lines.

Above: tenfold enlargement of the strip of sound film. A pure tone of 730 c/s is recorded upon the film according to the amplitude system.

Below: spectra of strips of film of different lengths.

a) Length 33 mm = 0.11 sec. The width of the lines is still determined by the finite dimensions of the light source used.
b) Length 6.6 mm = 0.022 sec. The zero order exhibits the expected extra maxima. The width of the main line is 90 periods.
c) Length 4.0 mm = 0.01234 sec. The lines are clearly widened to 150 periods.
d) Length 2.3 mm = 0.0077 sec. The lines are very much widened, to 260 periods.

In *fig. 5* may be seen the spectrum of four strips of sound film of the amplitude system upon which a pure sine of 730 c/s is recorded. The length of the strips is 33, 6.6, 4.0 2.3 mm. respectively, corresponding to 80, 16, 9.7 and 5.6 periods and to times of 0.11, 0.022. 0.0134 and 0.0077 seconds respectively. The width of the main lines must therefore be 18, 90, 150 and 260 periods respectively.

In fig. 5*a* this width is still small in comparison to the widening caused by the finite dimensions of the light source which is not exactly a point. In 5*b* the widening is scarcely noticeable. Next to the zero order, however, the side bands are now clearly visible. The width of the main line in the zero order is exactly 1/8 of the distance between two orders, which is equal to 730 periods, and therefore corresponds to the expected width of 90 periods. The films *c* and *d* show, as was to be expected, a continually increasing widening. The higher orders are not visible on the photographs since their intensity is too slight. Therefore upon shortening the strip of film the spectrum becomes steadily less sharp, so that fine structure can no longer be resolved. The well-known rule of grating spectroscopy, that the resolving power of a ruled grating is directly proportional to the width of the grating, is thus encountered here in the case of the spectra of short sections of film.

### The spectrum of a warble tone

Warble tones are tones whose frequency varies periodically. They are used in acoustics in measurements of reverberation, and derive their name from the sound impression which they give.

The remarkable thing about these warble tones is that their Fourier spectrum consists of a number of discrete lines lying on both sides of their average frequency. In *fig. 6* may be seen the spectrum of a repeated impulse with periodically changing distances. When this spectrum is compared with that of fig. 4 it may be seen how each line has been more and more clearly resolved into a number of lines according as the order increases.

This phenomenon recalls the phenomenon of ghosts in grating spectroscopy. Almost every optical grating gives several weak extra lines called ghosts on both sides of the main line of the diffraction spectrum. These lines are due to periodic changes in the distance between the rulings of the grating, which in turn are due to periodic irregularities in the transmission mechanism of the ruling machine.

A similar phenomenon is met with in the frequency modulation in radio waves, whereby several side bands occur in addition to the carrier wave.

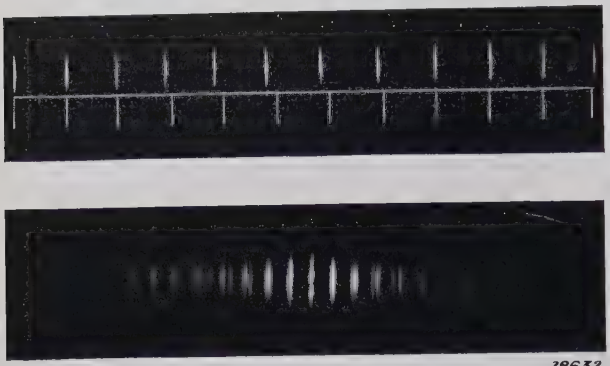


Fig. 6. Spectrum of a warble tone.
Above: tenfold enlargement of the strip of sound film, upon which a periodic impulse with periodically varying frequency is registered. Average frequency 200 c/s. The maximum or minimum of the frequency occurs 23 times per second.
Below: The spectrum of the warble tone. If this is compared with the spectrum of fig. 4, it will be seen that the higher orders have split into a number of lines.

### The determination of the frequency characteristic of a system from the manner of motion under the influence of an impulse

The characteristics of an amplifier can be determined by the frequency characteristic. This is the ratio of output to input signal as a function of the frequency. For faithful reproduction it is essential that this ratio be independent of the frequency.

An amplifier may, however, be characterized in another way, namely by giving the amplifier a short impulse and registering on an oscillograph the consequent voltage occurring at the output terminals as a function of the time. If the amplifier is ideal the same impulse will appear in the output signal, *i.e.* on the oscillograph. If the apparatus is not ideal, and if, for example, the frequency characteristic exhibits a more or less pronounced maximum, instead of the impulse, a more or less damped oscillation is seen on the oscillograph, having a frequency practically equal to the resonance frequency. It is well known that the frequency characteristic can be deduced from this oscillogram. What does it mean when we give an amplifier a single impulse?

In the foregoing we have seen that a periodic impulse contains the main tone and the overtones all in equal intensities. If now we continually increase the time intervals at which the impulse is repeated, the main frequency becomes steadily lower and the overtones, which all have the same intensity and are equidistant in the frequency spectrum, begin to lie closer and closer to each other. If the time interval becomes infinitely great, only one impulse remains, and the series of lines passes over into a continuous spectrum in which all frequencies are equally strongly represented. The giving of a single impulse therefore comes down to the simultaneous application of all frequencies.

If the amplifier has a resonance in the frequency characteristic, the frequency corresponding to it will appear relatively strongest in the output signal. The resulting voltage will no longer have purely the form of an impulse, but will show a periodicity corresponding with the resonance frequency.

Another example may serve to clarify the relation between frequency characteristic and output signal for a single impulse. We take an ordinary pendulum and apply to it a periodic force. The pendulum will then move with the same period. For frequencies below the characteristic frequency this movement will be small in amplitude. As the frequency of the force applied rises and approaches the characteristic frequency of the pendulum, the amplitude of the pendulum will increase steadily and decrease again for frequencies higher than the characteristic frequency of the pendulum. In this way we have determined the frequency characteristic of the pendulum. When we now give the pendulum a blow, *i.e.* apply a sudden force to the pendulum for a short time, it will not immediately move with a jerk and then return quickly to the position of, rest. The pendulum will rather begin to move with a finite velocity and then oscillating in its characteristic frequency return gradually to its position of rest.

This is precisely the same behaviour as above. By means of the impulse, forces of all frequencies in equal strengths are applied the pendulum. Because of the maximum in the frequency characteristic, however, the frequency corresponding to the maximum appears more strongly in the amplitude, and thereby leads to a periodic motion of the pendulum. According as the maximum of the frequency is more or less flat, the motion of the pendulum is more or less damped.

We may therefore determine the frequency characteristic of a system by resolving the oscillogram obtained with a sinusoidal input signal in the form of an impulse into its Fourier components. By means of the spectra method this latter is easily possible. In *fig.* 7 may be seen a strip of sound film registered by the amplitude system. A periodic impulse was here applied to a system with a characteristic resonance, and the output signal was recorded on the film. It may be seen that amplitude returns to zero in the form of a damped oscillation after every impulse. The Fourier analysis of the strip of film shows that the oscillation no longer contains the various overtones all with the same strength, but with a strength which is directly proportional to the amplification factor of the system for the frequency in question. In the diffrac-

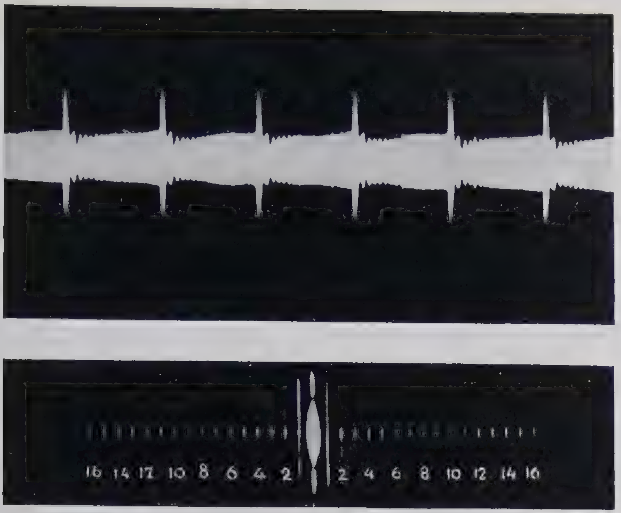


Fig. 7. Determination of the frequency characteristic.
Above: A periodic impulse of 250 c/s is applied to a system with a characteristic resonance in the neigbourhood of 4000 c/s. The input is then recorded according to the amplitude system. The amplitude is now not that of the pure impulse, but that of a damped oscillation (tenfold enlargement of the film).
Below: The spectrum of the strip of film. If this is compared with the spectrum of fig. 4, it may be seen that the higher orders are relatively stronger. This is due to the rise in the frequency characteristic for those frequencies (see fig. 8).

tion spectrum of fig. 7 this is manifested by the fact that the strength of the overtones is not proportional to that in fig. 4, but that here the strength after an initial decrease, increases again and reaches a maximum at about the 15th overtone. The frequency characteristic of the system is now obtained by measuring the intensity of every overtone, in fig. 4 and 7, and extracting the square root of their ratio. The characteristic is given in *fig. 8*.

It may be seen from this how it is possible to determine the whole frequency characteristic of a system from a strip of film several centimetres long. In principle a still much shorter length, namely that of one period, should even be sufficient. Then instead of a series of equidistant lines a continuous diffraction spectrum would be obtained, whose variation in intensity corresponds to the frequency characteristic of the system. The light intensity would then however be very small, and this would make the measurements difficult.

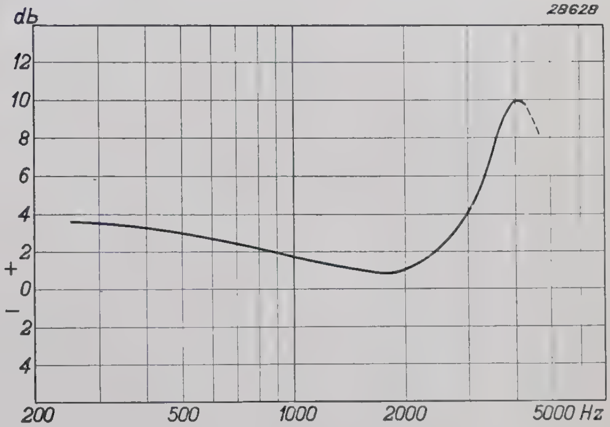


Fig. 8. The frequency characteristic calculated from the spectra of figs. 4 and 7. The ratio between the intensities of corresponding orders of figs. 4 and 7 is a measure for the corresponding ordinate of the frequency characteristic of the system for the frequency in question. By the measurement of intensities in the spectrum the whole frquency characteristic can be determined in this way.

# IMPULSE VOLTAGE INSTALLATIONS

by W. HONDIUS BOLDINGH. 621.319.5

By means of standardized components a series of generators may be build to give impulse voltages of 800 kV to 4 million volts, and impulse energies of 3.2 to 80 kilowatt seconds. The base of the apparatus is 2 × 2 metres, its height about 2 m/million volt. The condensers have an energy content of up to 80 wattseconds per cubic decimetre. A switch mechanism makes possible whole or partial series-parallel connection of the condensers in a simple way, so that impulses of lower voltage with the full energy can also be produced. Installations for impulse voltages up to 1200 kilovolts can be transported ready for use.

## Introduction

Since an impulse voltage installation was described in the first volume of this periodical [1]) considerable technical progress has been made in this field, and we shall discuss the result in the present article. This development coincided with the increasing interest on the part of power engineers in impulse voltage research, for which higher and higher voltages and especially larger and larger capacities of the impulse generator were demanded.

The knowledge that a large percentage of disturbances in high tension mains, power plants and transformer stations is caused by brief excess voltages due to atmospheric discharges has emphasized more and more the desirability of impulse voltage tests, of high tension installations ready for use as well as their separate elements. The great capacity toward earth of long transmission lines, of the high tension windings of large transformer units and of other test objects explains the demand for large impulse capacity. The charge of the generator must be high with respect to that necessary to raise the test object to the required potential, so that no excessif voltage loss will occur during the impulse.

Since as a rule the insulation of the test object to earth must be tested, standard generators will be constructed exclusively with one pole earthed, but in such a way that they can give positive as well as negative voltage with respect to earth.

In practice it is furthermore important that the whole impulse installation can be moved to any point of the high tension mains to be tested, without the necessity of elaborate assembly dismantling, so that the investigation need not be confined to the factory or laboratory.

For the examination of outdoor lines it is sometimes desirable to be able to use the full energy at a low voltage, which can be attained by connecting the impulse condensers wholly or partially in parallel. Then with the maximum energy an impulse of low voltage and high current can be produced, in order to burn through with this so-called surge current a defect caused with high tension, and thus bring it to light.

The above considerations led to the design of the impulse voltage generators to be described in this article. Although they naturally differ in many respects from the generators for high constant voltage which were developed for research on the problems of nuclear physics [2]), there are nevertheless many common structural features. The chief common characteristic is that by adequate designing of each composing part the main dimensions, even for very high voltages and energies could be kept within very narrow limits.

As for the impulse generators, it was made possible in this way to house an installation for several megavolts in a laboratory or factory hall of reasonable size, and on the other hand it was made possible to transport installations for up to 1.2 megavolts in working order.

## Scheme of the impulse generator

Before we go into the particulars of the circuit, we shall briefly recall the principle of the Marx circuit which is the one used here. A charging generator charges a number of condensers (the "impulse condensers") connected in parallel *via* suitable resistances to a high voltage with the condensers. As soon as a definite voltage is reached a series of spark gaps break down and the impulse condensers are suddenly connected in series. A voltage is obtained which is equal to the sum of the voltages of the impulse condensers, which now discharge (again through suitable resistances). A damping resistance prevents the occurrence of any oscillations on the voltage wave.

Even when we confine ourselves to unipolar impulse generators, there are in general two fundamentally different possible circuits for the charging generator: the symmetrical and the uni-polar circuit. *Fig. 1 a* and *b* give diagrammatically the principle of these two cases. (For the sake of simplicity the damping resistance is not drawn here). The symmetrical circuit is more often used, and from the stand point of insulation it is also the simpler. If the high tension transformer *T* gives a peak voltage $E_s$ then with the symmetrical charging generator (fig. 1*a*) each of the two supply connections is only at the potential $E_s$ (either plus and minus) with respect to earth. With the uni-polar charging generator, on the other hand, where the charging voltage 2 $E_s$ is obtained by cascade arrangement of the two rectifier valves (fig. 1*b*), the supply connection is at the full charging potential 2 $E_s$ with respect to earth. Therefore with the uni-polar charging generator more insulation is required especially since the polarity must be able to be reversed, and thus both terminals must be insulated for the full voltage of 2 $E_s$.

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[1]) A. Kuntke: Philips techn. Rev. **1**, 235, 1936.

[2]) A. Bouwers and A. Kuntke: Z. techn. Phys. **18**, 209, 1937; cf. Philips techn. Rev. **1**, 6, 1936 and **2**, 161, 1937.

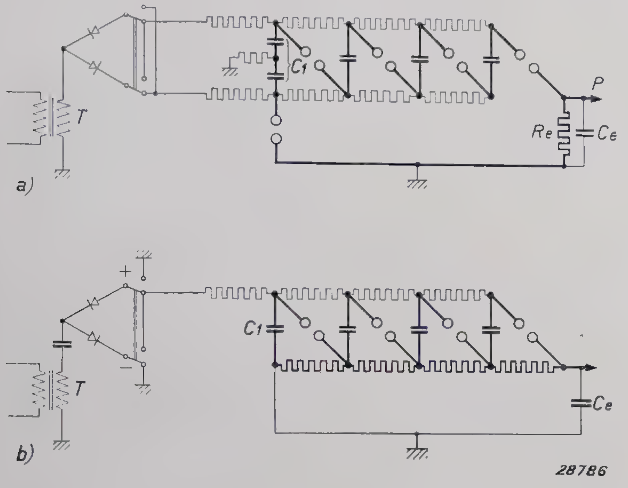

Fig. 1. Fundamental scheme of a uni-polar impulse voltage installation (four stages) *a*) with symmetrical charging generator, *b*) with uni-polar charging generator. *T* = high tension transformer, $C_1$ = first impulse condenser, $C_e$ = end condenser $R_e$ = discharging resistance. The test object is connected at *P*.

Nevertheless a uni-polar charging generator was chosen for the Philips impulse voltage installations, since it has various advantages.

1) Part of the charging resistances can also serve as discharging resistance (thick lines in fig. 1*b*). Apart from a saving in material by the omission of the special discharging resistance $R_e$ (fig. 1*a*) this has the advantage that there is no large current loop during the discharge: each condenser is discharged through its own discharging resistance. The external inductance which increases with the area of the current loop is in this way reduced to a minimum.
2) No spark gap to earth is necessary (*cf*, for contrast fig. 1*a*), since the first condenser $C_1$ is already uni-polarly earthed even during charging. In addition to the centre tap of $C_1$, the special arrangement for regulating the spark gap to earth, which must always be adjusted to half of the sparking potential of the other spark gaps, may also be omitted.

By the abolition of the spark to earth an important source of oscillations on the voltage wave is avoided, since $C_1$ is not first earthed by the break down of the spark earth. Both of the arguments mentioned above contribute to obtain a smooth voltage wave without using large damping resistances causing excessive voltage loss, or any other complication.

In designing an impulse generator the voltage of the charging generator, *i.e.* the voltage per stage, is very important, since it determines the number of stages for the total voltage required. The charging generator in the Philips impulse voltage installations gives a maximum charging voltage of 200 kilovolts. It is so generously designed that even at the highest impulse energy the desired rapid succession of impulses (for instance every 10 seconds) can be obtained. The charging generator, as well as the impulse generator itself, is mounted on a base plate, which may be provided with wheels, so that it can easily be transported. Because of the uni-polar circuit, in which the full direct voltage of 200 kilovolts with respect to earth is obtained, the charging generator by itself (separate from the impulse generator) may very well be used for other purposes, such for example as the testing of cables.

## Main components of the installations

In the construction of the impulse generators to be described here the use of "high-tension Philite", which has already been described in this periodical [3]), has been of great value. This insulating material has a break-down strength of 30 kilovolts/mm, and may therefore be compared with the best high-tension porcelain. It has thereby the advantage of very small dimension tolerances so that it can be made with screw-threads. "Philite" is used in the Philips impulse generators chiefly in the form of cylinders, with or without a bottom and with or without a flange, which may be screwed together and to other composing elements. The cylinders are made in two sizes: with a diameter (not including the flange) of 18 and 30 cm and a height of 11.1 and 22.2 cm respectively, and used for insulating supports, condensers (with the necessary number of condenser units connected in series simply piled up in the "Philite" cylinder), for resistances, etc.

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[3]) L. L. C. Polis: Philips techn. Rev. 3, 9, 1938.

*Condensers*

The impulse condensers are naturally the most important parts of the impulse generator. Their shape and size determine the design of the whole installation. The fact that great progress has been made in this field is obvious when the apparatus described here is compared with that of two years ago. Then condensers for 150 kilovolts were used with a capacity of 0.01 μF; the energy content ($^1/_2\, C.V^2$) per stage therefore amounted to 112.5 W sec. The length was 30 cm, while the diameter was 18 cm, so that 15 W sec per dm$^3$ is taken up. This was then a very high figure.

At present condensers for 200 kilovolts maximum working voltage are used with a capacity of 0.125 μF, which can therefore take up 2500 W sec. with a length of 48 cm and a diameter of 30 cm. With a condenser length of 70 cm these values rise to 0.2 μF and 4 kilowatt sec., which corresponds to *80 W sec/dm*$^3$. These condensers, whose length and therefore energy content can be made still greater, can easily meet present requirements as to impulse energy at high tensions, without it being necessary to connect several of them in parallel.

For impulse generators with smaller energy, for instance for educational purposes, smaller condensers are used (see in *table I* at 800 and 1200 kilovolts). They are built up out of the previously mentioned "Philite" rings 18 cm in diameter. A five-ring condenser of this type for 200 kilovolts has a capacity of 0.04 μF, *i.e.* an energy content of 800 W sec. Such condensers are used especially in constant voltage cascade generators.

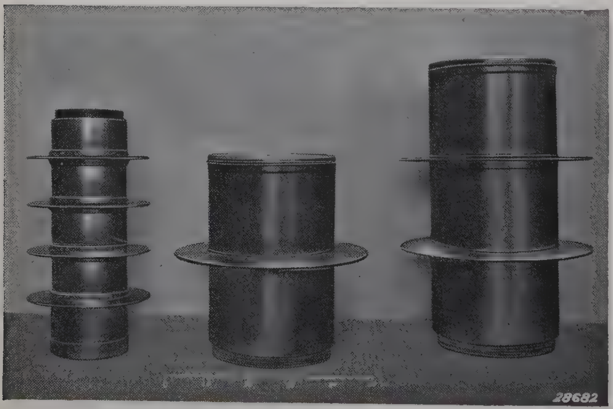

Fig. 2. Impulse condensers for 200 kV. *a*) 0.04 μF, 800 W sec; *b*) 0.125 μF, 2.5 kW sec; *c*) 0.2 μF, 4 kW sec.

The three types of condensers for 200 kilovolts, of 0.8, 2.5 and 4 kW sec respectively, are shown in *fig. 2.*

A remarkable characteristic of these condensers is that they are short circuit proof. They can be short circuited in the fully charged state without any series resistance. If this is done with a condenser as in fig. 2*b* in which 2500 W sec are thereby transformed into heat (600 cal) in a few microseconds, and if the discharge voltage is recorded, it will be seen from the damped oscillation which appears that the internal resistance of the condensers is less than 0.5 Ohm, and the inductance at the most 0.7 μH at a frequency of about 10$^6$ c/s.

In order to be able to obtain the required steepness of the wave front, it is desirable to employ a so-called end condenser. The duration of the wave front, $t_s$, which the voltage at the test object needs to reach its maximum value, is determined approximately by the relation:

$$t_s = 2\, R_d \cdot C_p. \quad \cdots\cdots \quad (1)$$

It will be smaller the smaller the total capacity $C_p$ in the circuit, and the smaller the total damping resistance $R_d$. In order to test all objects with about the same standardized duration of the wave front $t_s$, the latter could be regulated only by changing the damping resistance. With test objects with small capacities a large damping resistance would then be necessary. An upper limit is, however, prescribed for the damping resistance in connection with the permissible voltage drop: $R_d$ may not amount to more than 10 per cent of the discharging resistance $R_e$. The latter is already limited: its value is determined mainly by the standardized value of the time to half value of the wave tail $t_h$, and by the capacity $C_s + C_p$ of the generator (impulse capacity and load capacity) according to the formula:

$$t_h = R_e \cdot (C_s + C_p) \ln 2. \quad \cdots\cdot \quad (2)$$

In generators with a high impulse capacity therefore the discharging resistance as well as the damping resistance must be small. The smaller the latter resistance can be made the better, from the standpoint of voltage loss.

It is therefore preferable to regulate the time $t_s$ by the addition of the end condenser already mentioned. This may then have so large a value that the capacity of the test object has little influence within wide limits on the time $t_s$. The total loading capacity, however, may also not be too great since this also causes voltage drop. 20 per cent of the impulse capacity is accepted as a maximum value. The end condenser is then also always considerably smaller than the impulse condenser. In the Philips impulse voltage installations it consists of units of small diameter, for instance for 400 kilovolts, which may be connected in series or in parallel as desired. With test objects of large capacity the end condenser can of course be omitted.

### *Resistances*

While formerly liquid or carbon resistances were commonly used because of the high value of the resistance necessary to obtain the normal wave shape with the small impulse capacities then in use metal resistances can and must always be used now with the so much greater impulse energies. The resistance necessary for charging, discharging, damping and measuring are all mounted in dust-proof insulating material, and are of such generous dimensions that no excessive heating occurs, even with the highest impulse energies and short impulse intervals.

While the resistances which serve exclusively for charging may be wound in the ordinary way, the smallest possible inductance must be attained for the damping, discharging and measuring resistances. The damping resistance which, as we have seen, must be small in connection with the voltage drop, must on the other hand be large enough to insure the non-periodicity of the circuit $C_s - R_d - C_p$. For this the following condition is valid as an approximation:

$$R_d > 2 \sqrt{L/C_p}, \quad \cdots\cdots (3)$$

where $L$ is the total inductance of the circuit in question. It was possible to reduce self-induction of the damping resistance to such a low value that its resistance value can even be chosen smaller than the permissible limiting value of 10 per cent of the discharging resistance.

The total damping resistance is subdivided in such a way (see fig. 4) that each impulse condenser is connected in series between two equal sections of it. The damping is hereby so large that no high frequency oscillations on the main wave can occur in each separate stage due to parasitic extra capacities.

In order to be able to discharge the impulse condensers under all circumstances even without an impulse on the test object, an earthing resistance is built into the charging generator (not shown in fig. 1). This resistance has such dimensions that if necessary it can take up the full energy of all the impulse condensers together. The earthing switch earths the whole installation automatically when charging is interrupted.

### Construction of the impulse generator

The impulse generator consists of four columns, in each of which condensers and insulators are mounted alternately one above the other. The condensers are connected through resistances in such a way that the Marx circuit is built up in the form of a screw (see *fig. 3*). With this method of construction any number of stages may be completed, and

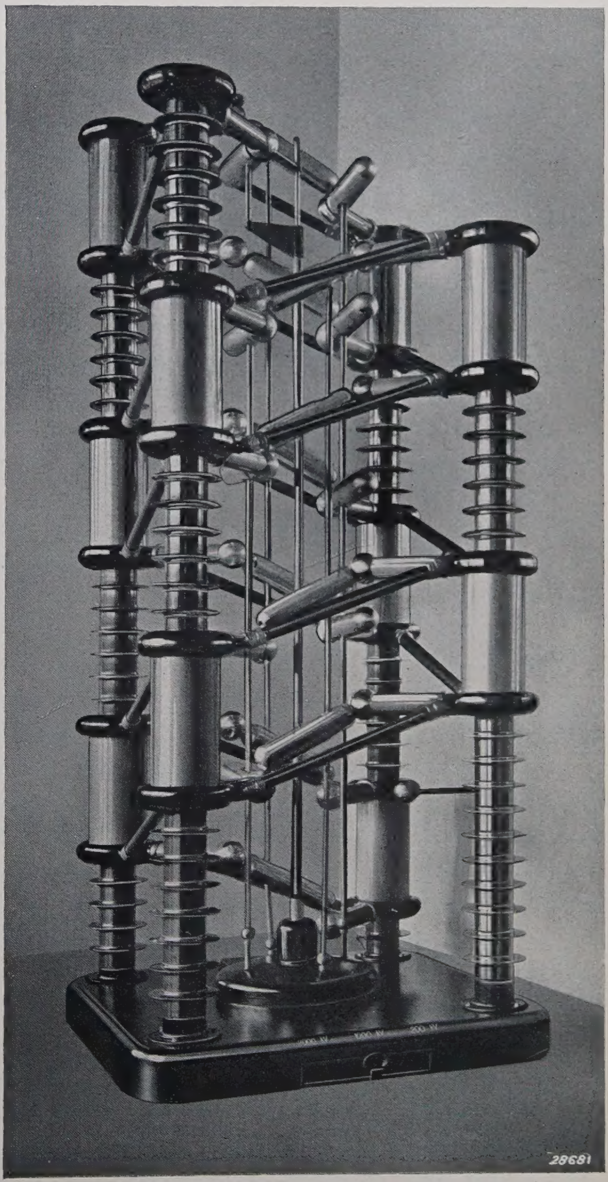

Fig. 3. Impulse generator with a impulse energy of 25 kW sec, commutable for 2000, 1000 and 200 kV (with 0.0125, 0.05 and 1.25 μF respectively). Height 4.5 m, base 2x2 m. In this type the large "Philite" cylinders are not yet used, so that the condensers may easily be distinguished from the insulators.

others added later, without increasing the necessary floor space, which is always 1x2 m. For reasons which will discussed later, the preferred number of stages will be as a rule a multiple of four, and therefore the impulse voltage will be a multiple of 800 kilovolts. In *table I* (page 316) the data are given of a series of impulse generators for different voltages, assembled with the three types of condensers shown in fig. 2.

The compact construction of the generators, which is illustrated by the main dimensions given in the table, has besides to purely spacial advantages the additional satisfactory result that, aside from the above-mentioned reduced inductance of the damping resistances, the remaining inductance in the circuit in question is also small.

The damping resistances are mounted at the top and bottom of every impulse condenser, and each has a switch arm. In this way every condenser is provided with two switch arms mounted at to top and the lower one of which serves as spark gap, while both together can connect the condenser in parallel with its predecessor. The spark gaps can be adjusted by remote controlled simultaneous motion of all the spark gap arms by means of five insulating bars (see in fig. 3 in the middle between the four columns). The middle one of these bars always serves the last, highest spark gap, the other four serve the other spark gaps and at the same time they serve to connect the impulse condensers wholly or partially in parallel by means of the second series of switch arms which are coupled in pairs with the spark gap arms.

## Possibilities of commutation

In *fig. 4* the different possibilities of commutation are drawn for the case of a generator with 8 stages, *i.e.* for 1600 kilovolts. The switch arms with the same numbers, see fig. 4*a*, are controlled by a common bar (due to the screw-shaped construction they lie vertically above each other). By means of bar *I* condenser *1* is connected in parallel with *2*, and *5* with *6*, while by bar *III*, *3* is put in parallel with *4*, and *7* with *8*, see fig. 4*b*. At half voltage a fourfold capacity is now obtained. If now by means of bar *II* condenser *2* is put in parallel with *3* and *6* with *7* (fig. 4*c*) there are then two groups each of four condensers in parallel, so that 1/4 of the total voltage can be reached (400 kilovolts) with 16 times the original capacity. Finally by means of bar *IV* *4* and *5* can also be connected in parallel (fig. 4*d*) so that a surge voltage of 200 kilovolts with a capacity 64 times the original capacity is obtained.

It is clear that all the possibilities of commutation can only be utilized at nominal voltages which are a multiple of 800 kilovolts, *i.e.* when the number of stages is a multiple of four. Table I gives an ideal of the voltages and capacities which may be obtained by commutation.

*Fig. 5* is a photograph of a commutable impulse generator for 16 kW sec in the present form with

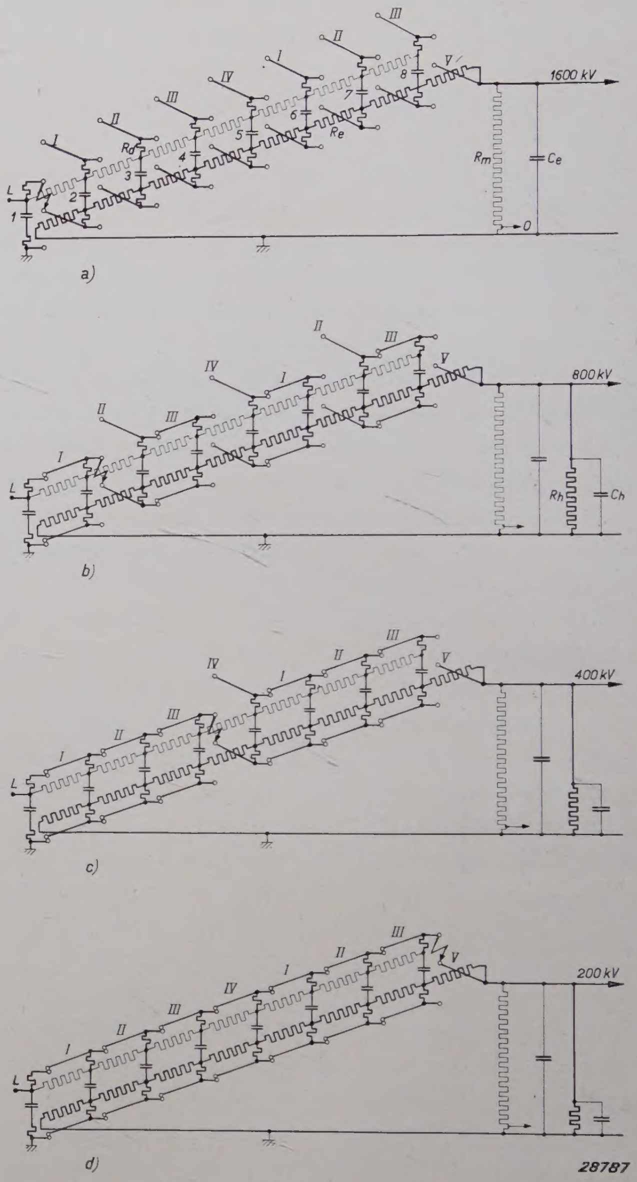

Fig. 4. Diagram of an impulse generator which can be commuted for voltages of 1600, 800 400 and 200 kV with the full surge energy in each case. The circuit which is actually built up in the form of a screw is shown here "unwound". The switch arms *I*, *II*, ... are operated by five bars (visible in fig. *3*). The charging generator is connected at *L*. $R_d$ = damping resistances, $R_e$ = discharging resistances, $R_m$ = measuring resistances, $C_e$ = end condenser, $C_h$ = auxiliary condenser, $R_h$ = auxiliary end resistance. The cathode ray oscillograph is connected at *0*. *a*) All condensers, *1*, *2*, ... *8*, in series. *b*) Switch arms *I* and *II* closed: four groups of two condensers in parallel, 800 kV. *c*) Switch arm *II* also closed: two groups of four condensers in parallel, 400 kV. *d*) Switch arm *IV* also closed: all eight condensers in parallel, 200 kV. The ignition spark gap is indicated in each case by a zigzag arrow.

Table I Data of the Philips impulse generators

| Nominal voltage . . . | kV | 800 | | | 1200 | | | 1600 | | 2400 | | 3200 | | 4000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Commutation voltages . | kV | 400/200 | | | 600/200 | | | 800/400/200 | | 1200/600/200 | | 1600/800/200 | | 2000/1000/200 | |
| Stages of 200 kV . . | — | 4 | | | 6 | | | 8 | | 12 | | 16 | | 20 | |
| Energy per stage . . . | kWsec | 0.8 | 2.5 | 4.0 | 0.8 | 2.5 | 4.0 | 2.5 | 4.0 | 2.5 | 4.0 | 2.5 | 4.0 | 2.5 | 4.0 |
| Capacity per stage . . . | $\mu$F | 0.04 | 0.125 | 0.2 | 0.04 | 0.125 | 0.2 | 0.125 | 0.2 | 0.125 | 0.2 | 0.125 | 0.2 | 0.125 | 0.2 |
| Total energy . . . . . | kWsec | 3.2 | 10 | 16 | 4.8 | 15 | 24 | 20 | 32 | 30 | 48 | 40 | 64 | 50 | 80 |
| Total capacity . . . . | in $10^3$ pF | 10 | 30 | 50 | 7 | 20 | 33 | 16 | 25 | 10 | 17 | 8 | 12.5 | 6.25 | 10 |
| Cap. at half voltage . . | in $10^3$ pF | 40 | 125 | 200 | 27 | 85 | 130 | 62.5 | 100 | 40 | 70 | 30 | 50 | 25 | 40 |
| Cap. at quarter voltage . | in $10^3$ pF | | | | | | | 250 | 400 | 170 | 270 | 125 | 200 | 100 | 160 |
| Cap. at 200 kV . . . . | in $10^3$ pF | 160 | 500 | 800 | 240 | 750 | 1200 | 1000 | 1600 | 1500 | 2400 | 2000 | 3200 | 2500 | 4000 |
| Height . . . . . . . . | m | 2.3 | 2.3 | 2.6 | 3.0 | 3.0 | 3.4 | 3.7 | 4.2 | 5.1 | 5.8 | 6.5 | 7.4 | 7.9 | 9.0 |
| Min. height of room . . | m | 3.3 | 3.3 | 3.6 | 4.5 | 4.5 | 4.9 | 5.7 | 6.2 | 8.1 | 8.8 | 10.5 | 11.4 | 13.0 | 14.0 |
| Weight . . . . . . . . | kg | 1200 | 1700 | 1800 | 1500 | 1950 | 2100 | 2200 | 2400 | 2700 | 3000 | 3200 | 3600 | 3700 | 4200 |

large “Philite” cylinders. The dimensions indicated in table I refer to this type.

The switch arms are controlled electrically from the control desk. The desired series parallel circuit is obtained after moving a handle in the base plate of the generator which can only be operated when the installation is completely earthed.

In order always to obtain the same form of impulse wave in agreement with the formulae mentioned, even with impulse condensers in parallel, the values of the discharging resistance $R_e$, damping resistance $R_d$ and the load capacity $C_p$ must be adapted to the larger impulse capacity $C_s$ obtained.

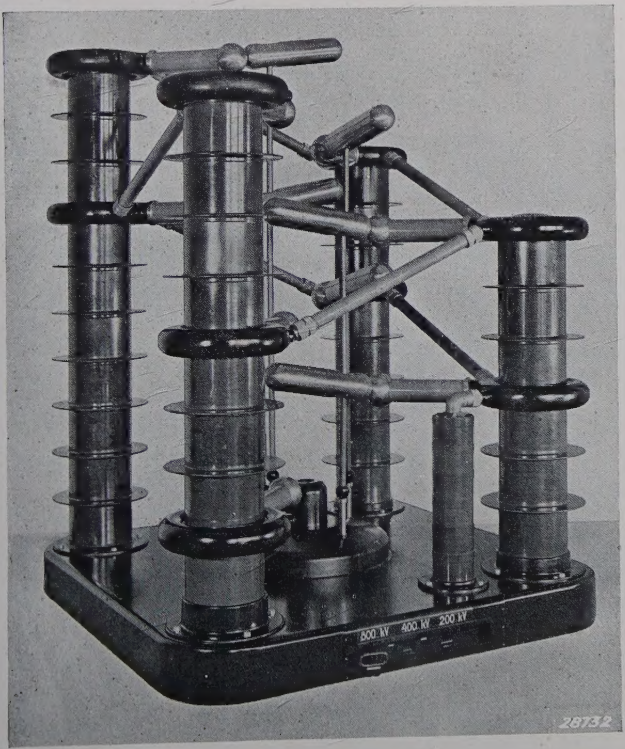

Fig. 5. Impulse generator with an impulse energy of 16 kW sec, commutable for 800, 400 and 200 kV (with 0.05, 0.2 and 0.8 $\mu$F respectively) in the present form with large “Philite” cylinders. Height 2.6 m.

In order to retain the original time of halve value of the wave tail with impulse condensers in parallel, the value of the discharging, (end) resistance must be reduced according to formula (2). From fig. 4 it is seen that when the impulse condensers are put in parallel, part of the discharging resistance (which are also the charging resistances) is short circuited. However this is not sufficient, there must also be an auxiliary end resistance (in fig. 4*b* indicated by $R_h$) in parallel with the test object.

Since the value of the damping resistance, as explained above, may not be more than 10 per cent of the end resistance, the damping resistance must also be reduced upon commutation. As may be seen from fig. 4 the parts of the damping resistance are automatically put in parallel, together with the corresponding impulse condensers, By this change in $R_d$, however, according to equation (1) the front duration $t_s$ of the impulse wave is affected. In order to retain the normal value of $t_s$ the end condenser might to be divided in the same way as the damping resistance and the parts connected in parallel. However it is often simpler to add an auxiliary condenser (indicated by $C_h$ in fig. 4*b*) such that the original value of $t_s$ is recovered. The auxiliary condenser $C_h$ and the auxiliary resistance $R_h$ are not combined in a single unit, in order to be able to omit the auxiliary condenser if necessary with test objects with large capacities, or to replace it by a smaller one.

The auxiliary end resistance which is used in the circuit for 200 kilovolts must be able to take up practically the entire impulse energy with the required impulse intervals.

### Measurement of the voltage

For the measurement of the course of the impulse voltage the cathode ray oscillograph is now generally recognized as the only suitable instrument. It gives not only the crest value, but makes it possible to follow the entire course of the voltage wave. The indication must of cource be a faithful reproduction of the phenomenon to be measured. Since we are here concerned with a single non-periodic phenomenon of very short duration it is preferable to use a resistance potentiometer above a capacitive one, such as is sometimes used.

It is obvious that the measuring resistance may only have a minimum inductance. The ordinary methods of measuring this latter cannot be used because of the high damping. For the determination of self-inductance of the measuring resistance a model is constructed in which the resistance wire was replaced by copper wire, still retaining the geometric form (which determines the inductance in the first instance).

In how far a true reproduction is obtained with the measuring resistance used may be seen most clearly from an oscillogram of a breakdown at the wave crest of an impulse, as is given in *fig. 6* together with an oscillogram of a normal wave.

Besides the impulse voltage itself the charging voltage may also be measured. Thanks to the unipolar circuit of the charging generator it is possible by means of a very large series resistance to indicate the charging voltage of the impulse condensers directly with a voltmeter on the control desk. This gives a more complete and more accurate check on the voltage during charging, than the measurement of the length of the spark, by which only the peak value of the charging voltage can be determined.

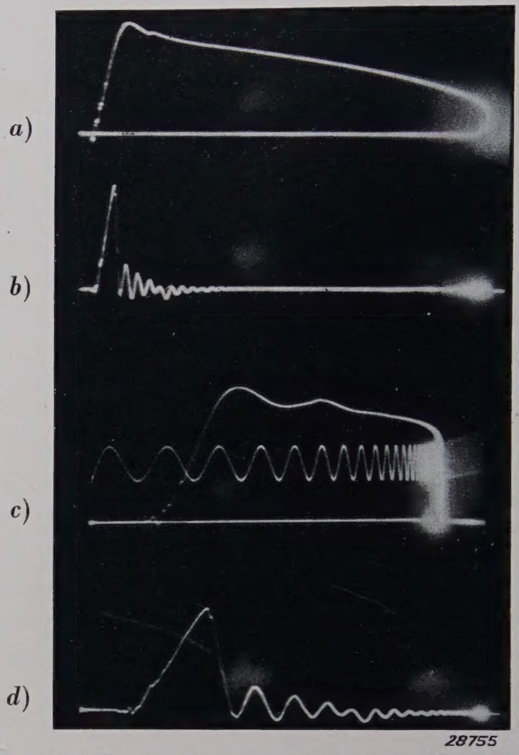

Fig. 6. *a*) Oscillogram of a normal 1.0/50 wave (duration of the front $t_s$ = 1.0 $\mu$ sec, time to half value of the wavetail $t_h$ 50 $\mu$ sec). *b*) Oscillogram of the same wave with breakdown at the crest. *c*) Like *a*) with larger time base. *d*) Like *b*) with larger time base. The time base is obtained by the exponentially decreasing voltage during discharge of a condenser, in *c* the time is recorded by means of a sinusoidal oscillation of $10^6$ c/s, in which therefore one period indicates 1 $\mu$ sec.

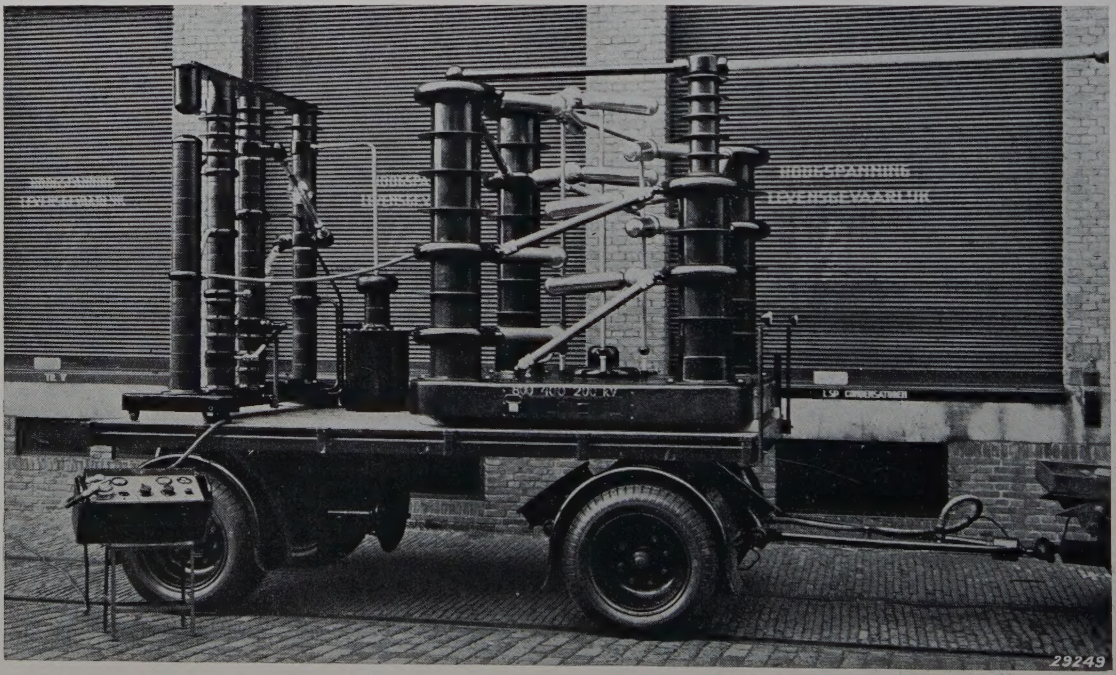

Fig. 7. Transportable impulse voltage installation with an impulse energy of 10 kWsec for 800 kV commutable for 400 and 200 kV. Surface of the trailer 2.20·4 m², total height from the earth 3.30 m.